Our Understanding of the Top Quark

(Fifteen Years After Its Discovery)

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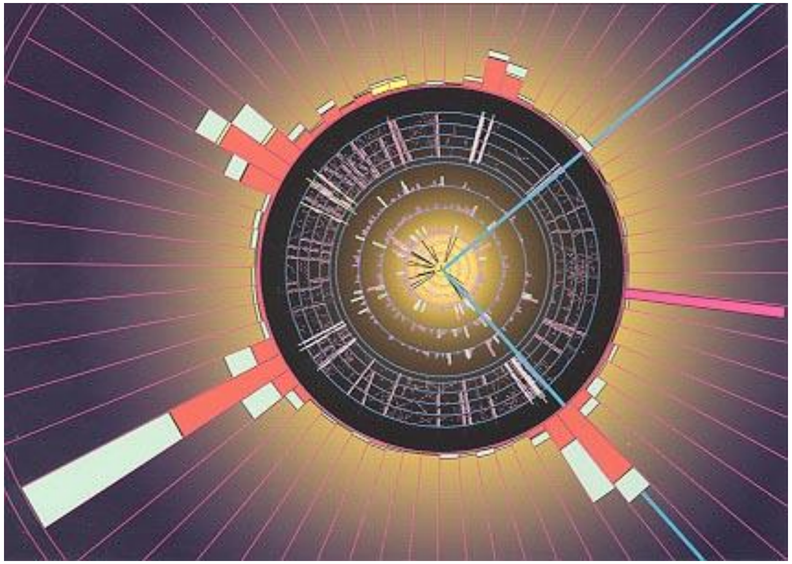
Outline

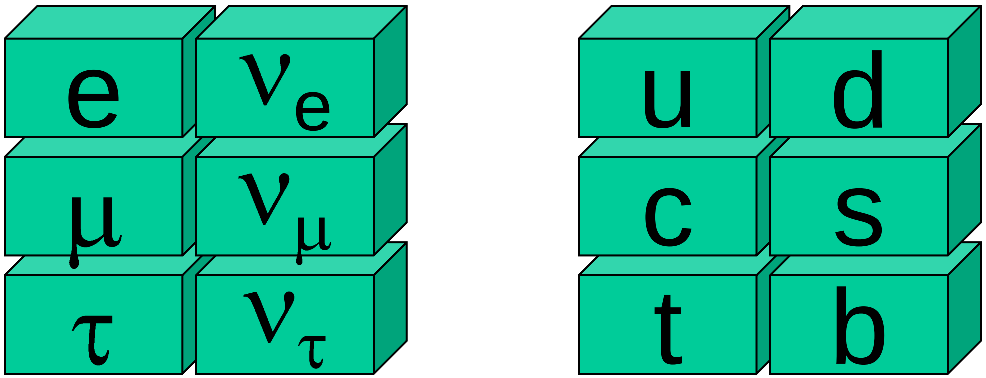
- Introduction
- Top quark production and decay
- Studies of Top quark production mechanisms
  - Top pair production cross section
  - Non SM production mechanisms
  - Single top production
- Studies of Top quark properties
  - Mass
  - Decay properties
  - Charge, Width, Spin
- Conclusions and Outlook



What is the World Made of?

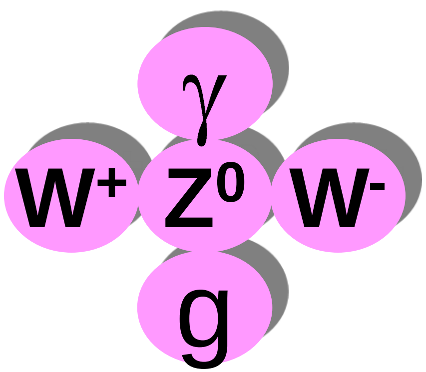
Standard Model (~1970)

ELEMENTARY CONSTITUENTS

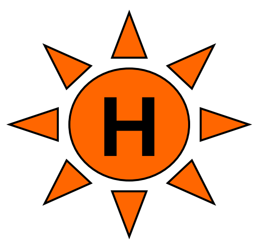


Strong	1
Electromagnetic	10^{-2}
Weak	10^{-6}
Gravity	10^{-40}

INTERACTIONS

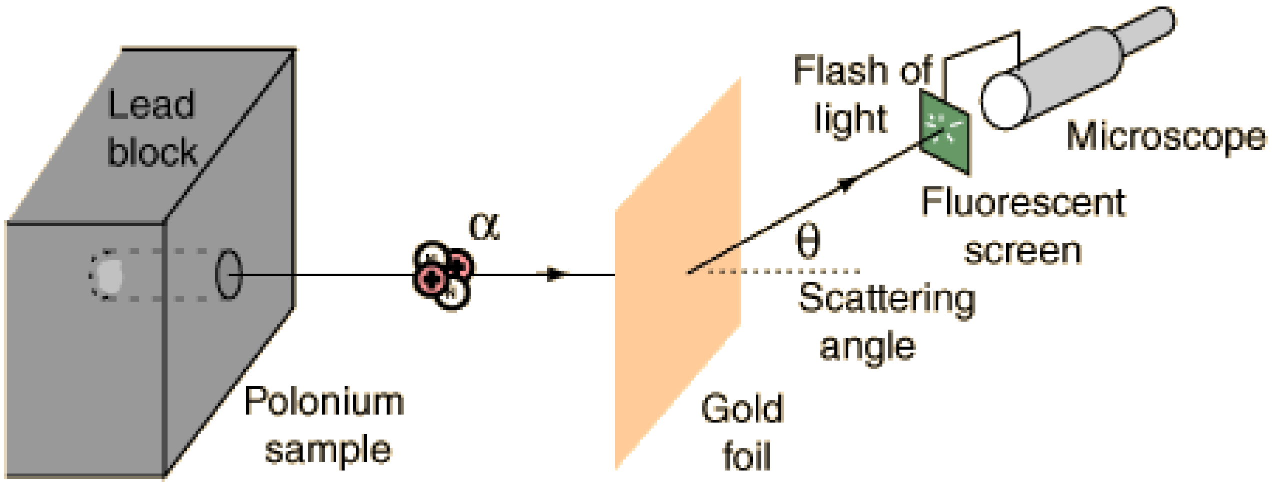


Higgs



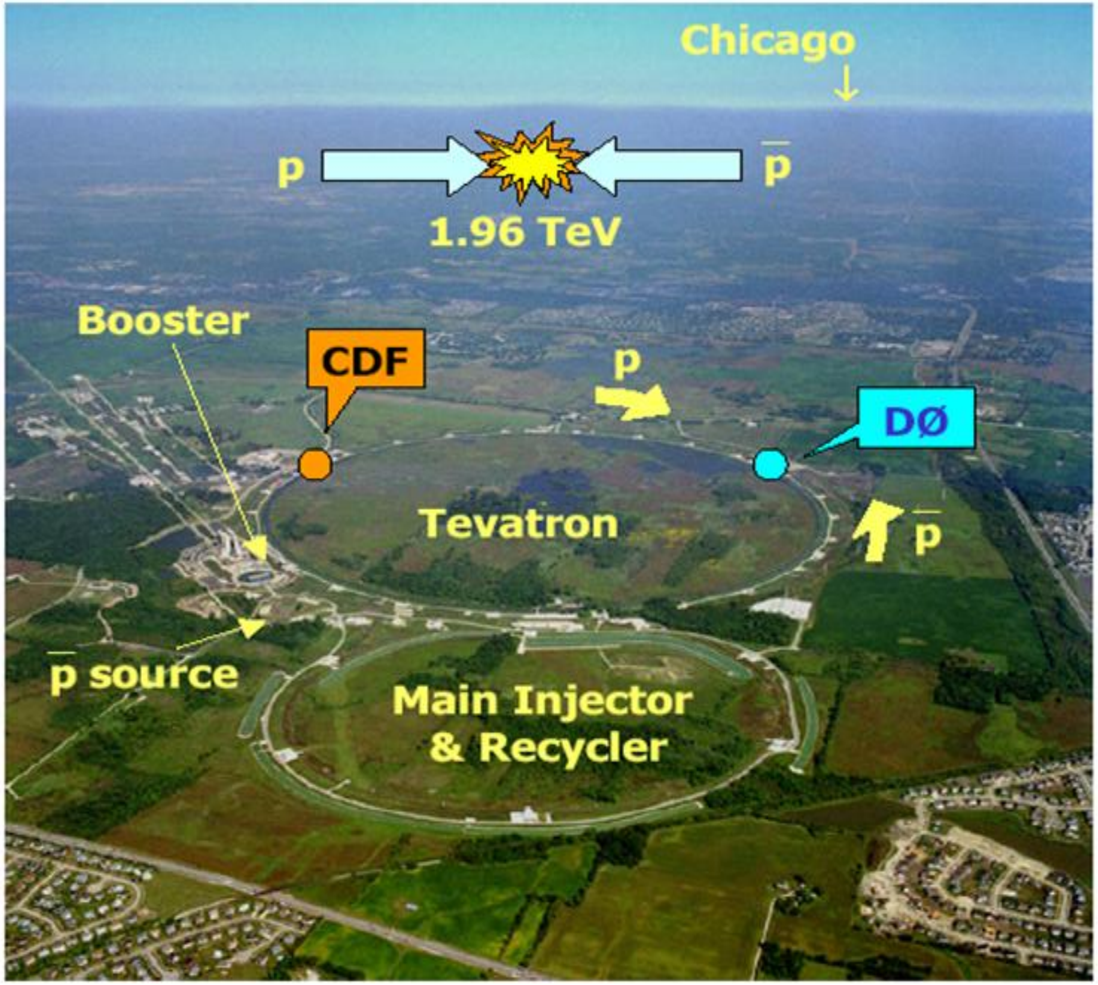
Rutherford Scattering

Alpha particles were allowed to strike a thin gold foil. Surprisingly, alpha particles were found at large deflection angles and ~1 in 8000 were even found to be back-scattered.



This experiment showed that the positive matter in atoms was concentrated in an incredibly small volume (10^{-15}m) and gave birth to the idea of the nuclear atom.

The Fermilab Tevatron Accelerator



p anti-p collider:

1992-96

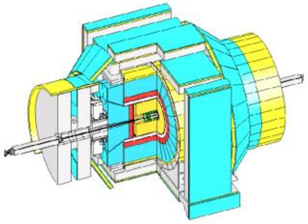
Run 1: 100pb^{-1}, 1.8TeV

2001-2011?

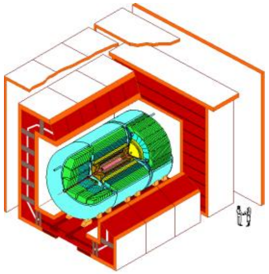
Run 2: ~12fb^{-1}, 1.96TeV

8fb^{-1} delivered

All we know about the top quark comes the Tevatron

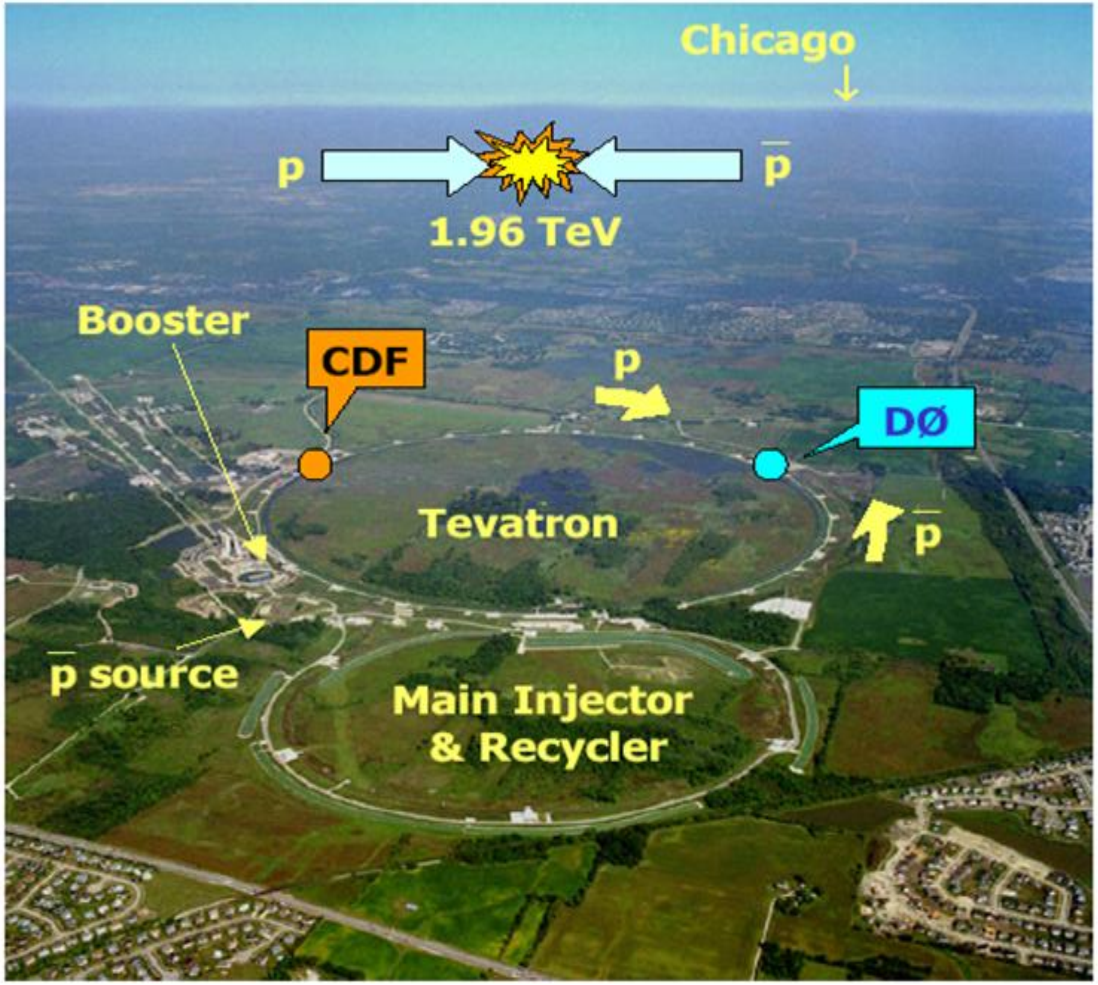


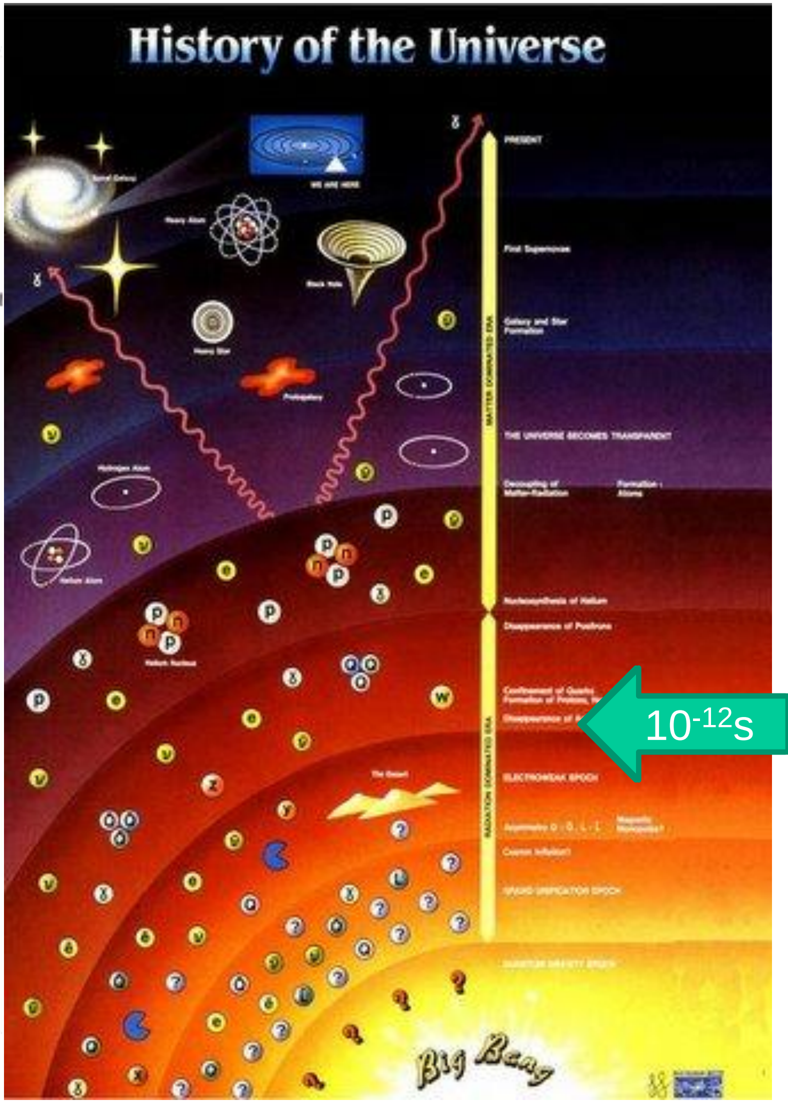
CDF



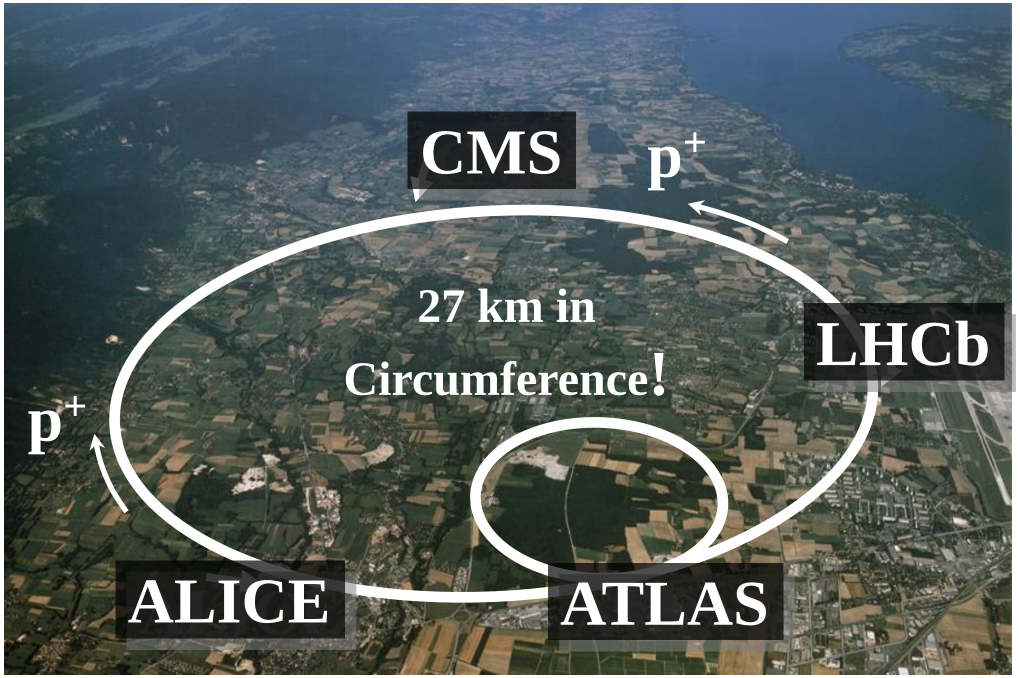
DØ

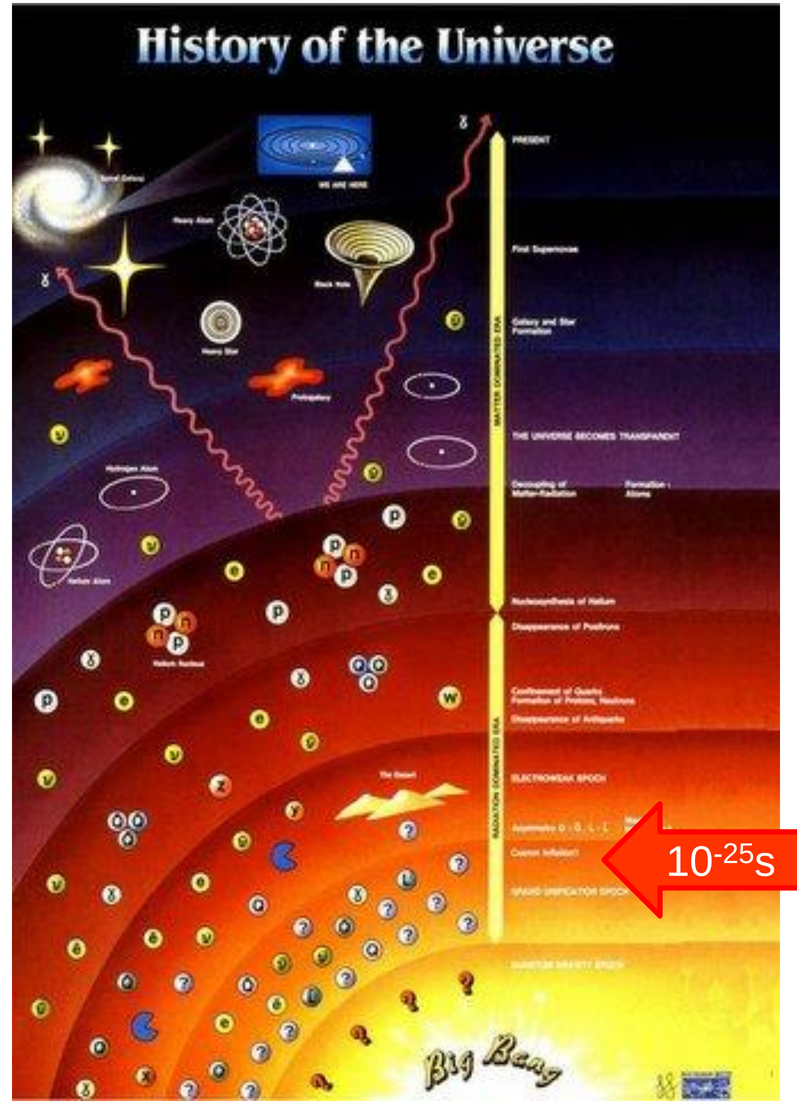
The Fermilab Tevatron Accelerator





The CERN LHC

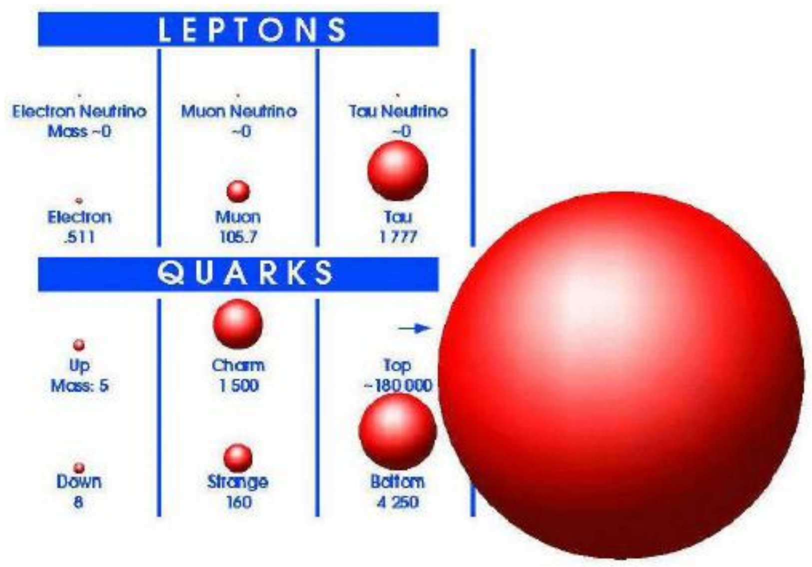




- 14TeV p-p collider
  - 1Hz top production rate
- Data delivered ~10μb^{-1} @ 900GeV
  - expect to collect 1fb^{-1} @ 7TeV during 2010-2011

Why study the Top Quark?

- Predicted by the SM and Discovered in 1995 by CDF and DØ
  - $m_t \sim 170$ GeV vs $m_b \sim 5$ GeV
- Top-Higgs Yukawa coupling $\lambda_t \approx 1$
  - may help identify the mechanism of EWSB and mass generation.
  - may serve as a window to new physics that might couple preferentially to top.

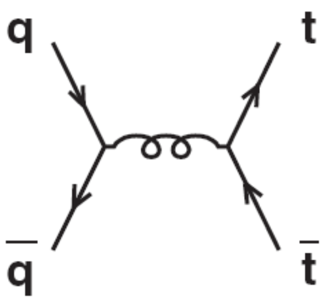


- Successful Tevatron top quark program
  - High precision measurements for the top quark mass, top pair production cross section and decay properties
- Some basic quantities still not measured precisely: spin, width, lifetime
- Electroweak single top quark production predicted by the SM, has been observed in March 2009, 14 years after the pairs observation.

Top quark pair production – strong interaction

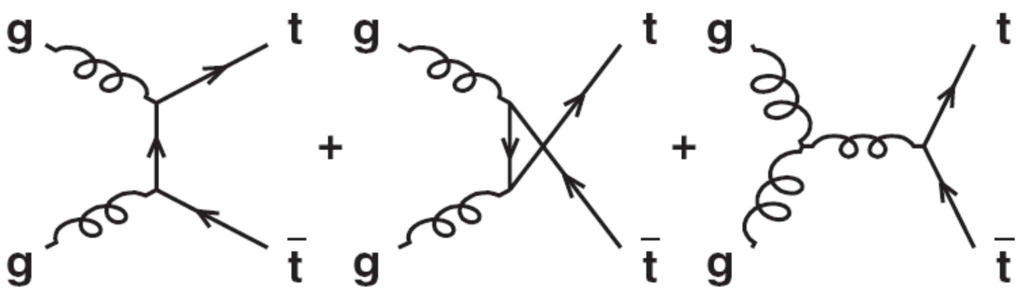
(qq annihilation)

$q\bar{q} \rightarrow t\bar{t}$



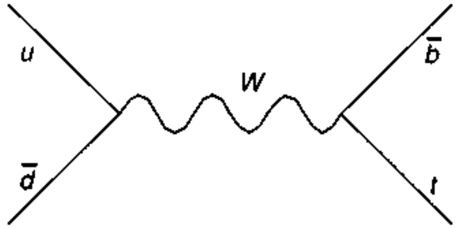
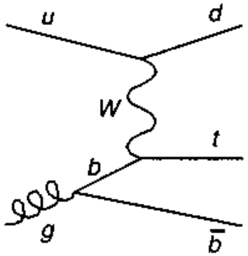
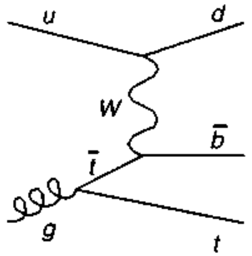
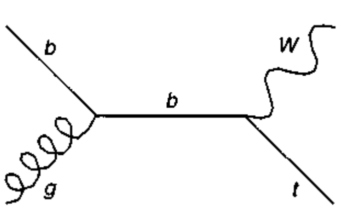
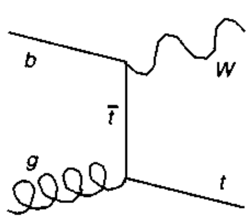
(gluon fusion)

$gg \rightarrow t\bar{t}$



	Run1(1.8TeV)	Run2(2TeV)	LHC(14TeV)
$q\bar{q} \rightarrow t\bar{t}$	90%	85%	5%
$gg \rightarrow t\bar{t}$	10%	15%	95%
x-sec(pb)	5.4	7	800 150 (@7TeV)

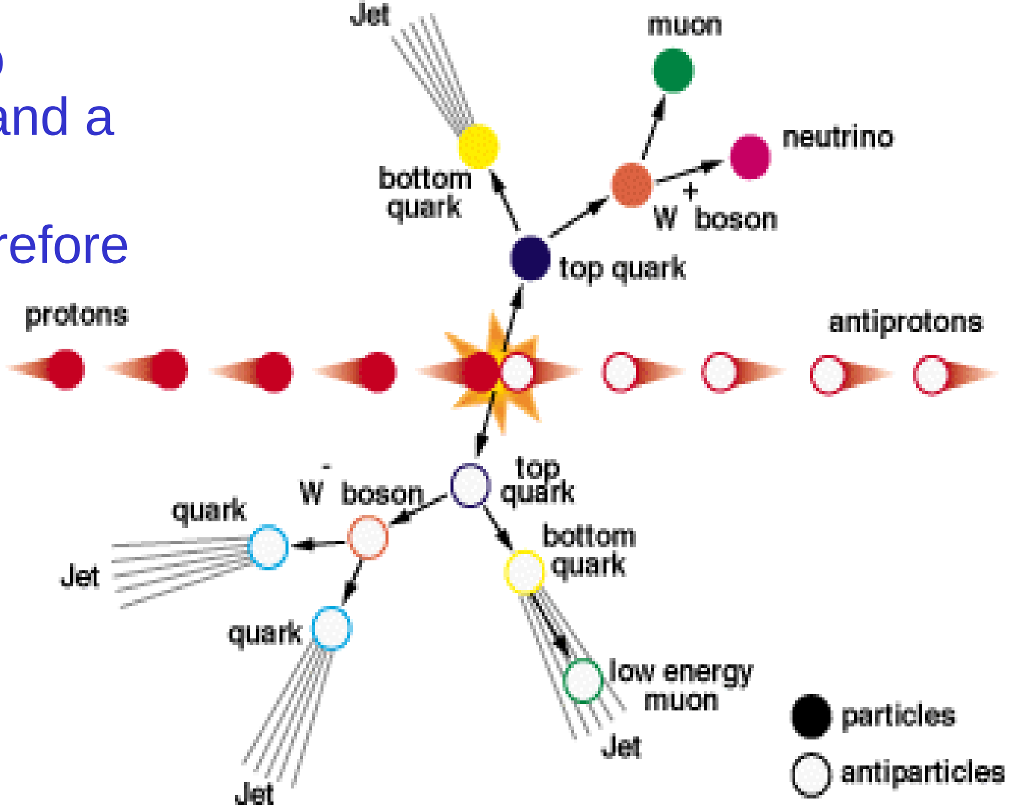
Single Top quark production – EW interaction

		Run2(2TEV)	LHC(14TeV) (7TeV)
(s-channel) $q\bar{q} \rightarrow t\bar{b}$		1pb	10pb 4pb
(t-channel) $qg \rightarrow q't\bar{b}$	 	2pb	250pb 60pb
(associated production) $gb \rightarrow tW$	 	negligible	60pb 10pb

Top-quark decay

- ~100% of the time, a top quark decays into a bottom quark and a W boson.
- The W boson can decay into two quarks or into a charged lepton and a neutrino.
- A Top-anti Top event should therefore have either:
  - 6 quarks
  - 4 quarks, 1 charged lepton and 1 neutrino
  - 2 quarks, 2 charged leptons and 2 neutrinos

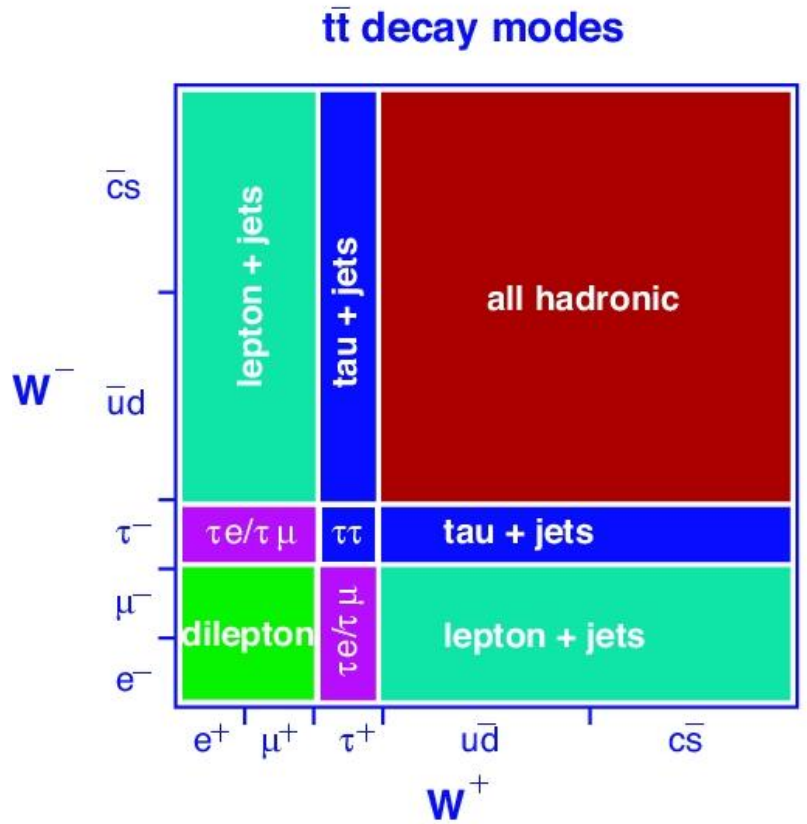
In all cases, 2 b-quarks are present in the event

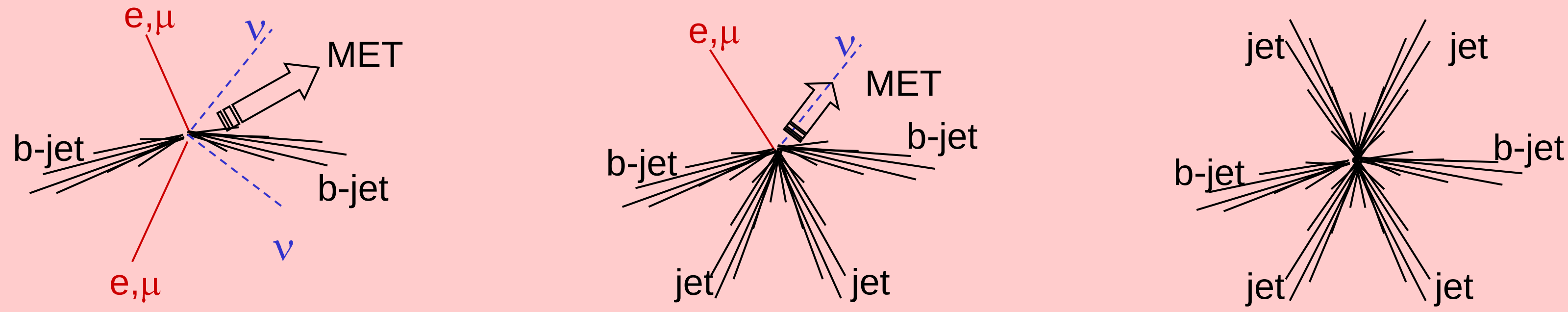


A Top Antitop Quark Event from the D-Zero Detector at Fermilab

Top Quark Decay Modes

"Lepton": electron or muon



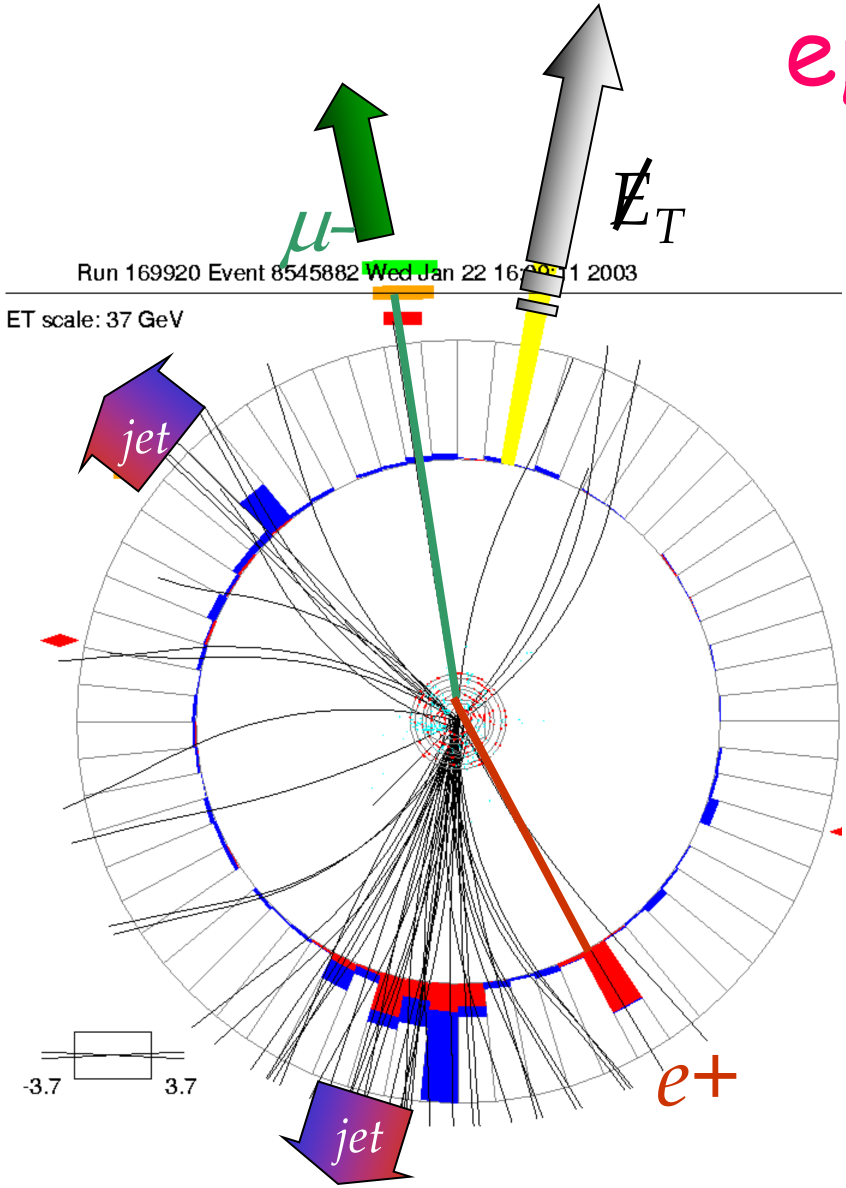


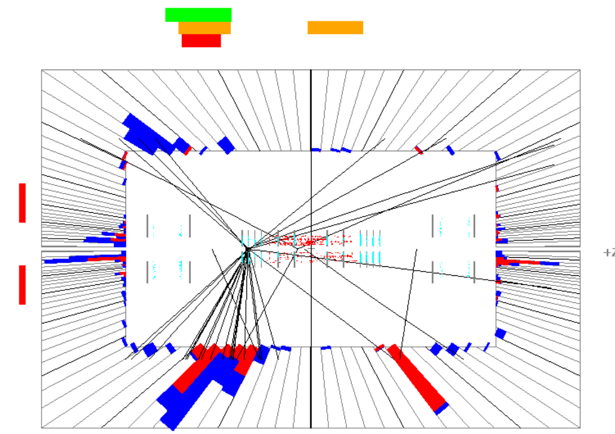
Dilepton
(BR~5%, low bckg)

Lepton+jets
(BR~30%, moderate bckg)

All-hadronic
(BR~46%, huge bckg)

eμ Top candidate

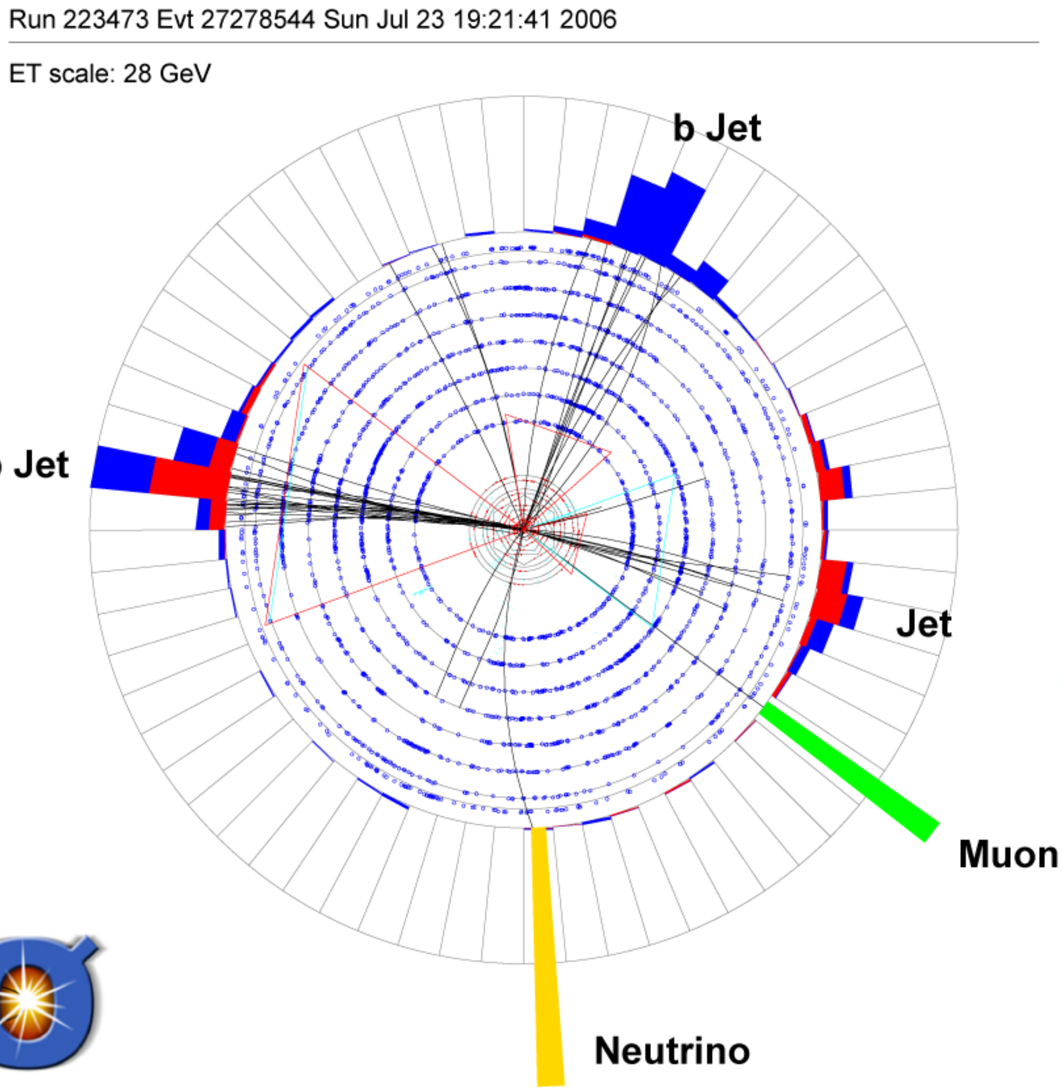


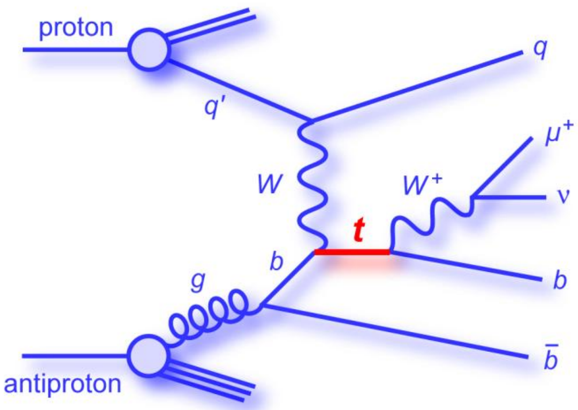


e+	P_T= 20.3
μ−	P_T= 58.1
j	P_T= 141.0
j	P_T= 55.2
$\not{E}_T$	91 GeV

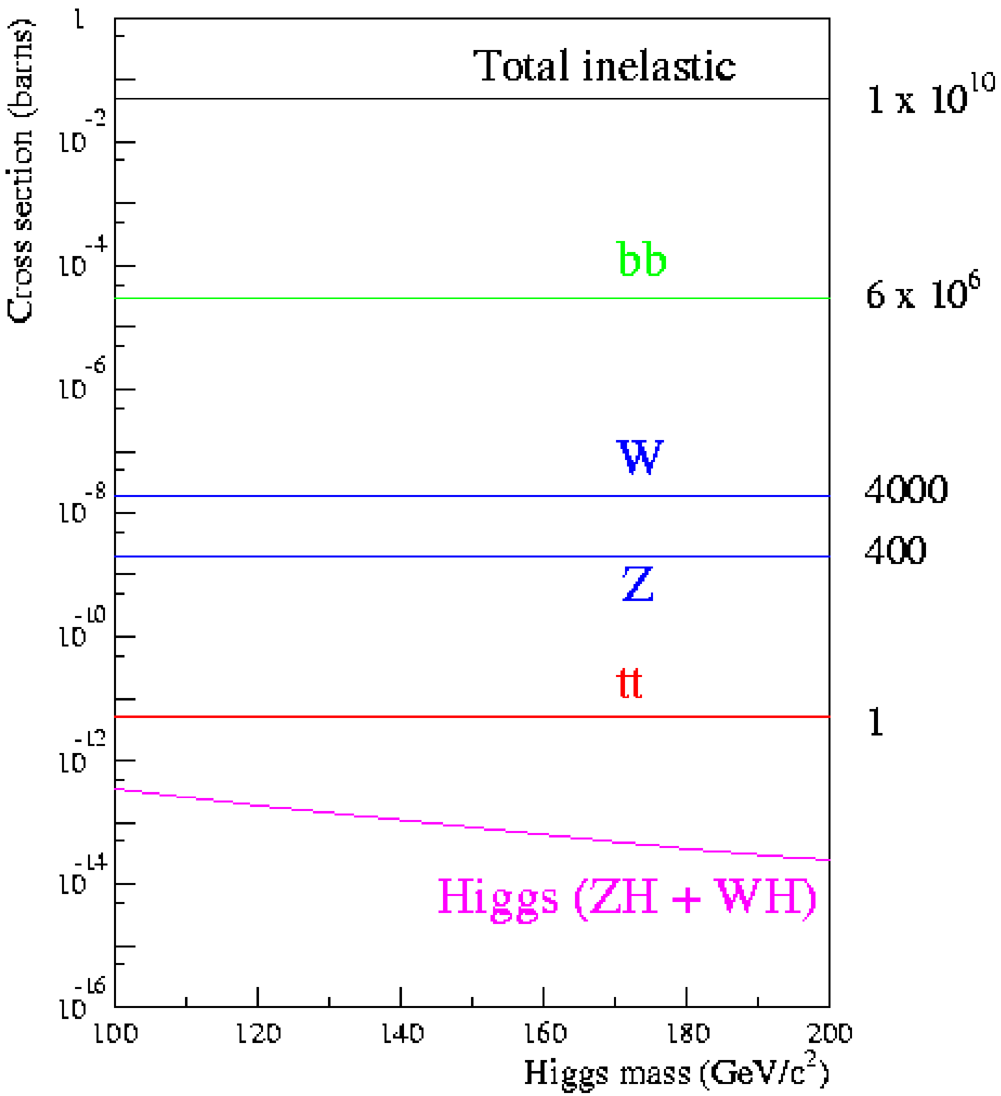
DØ Experiment Event Display

Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis





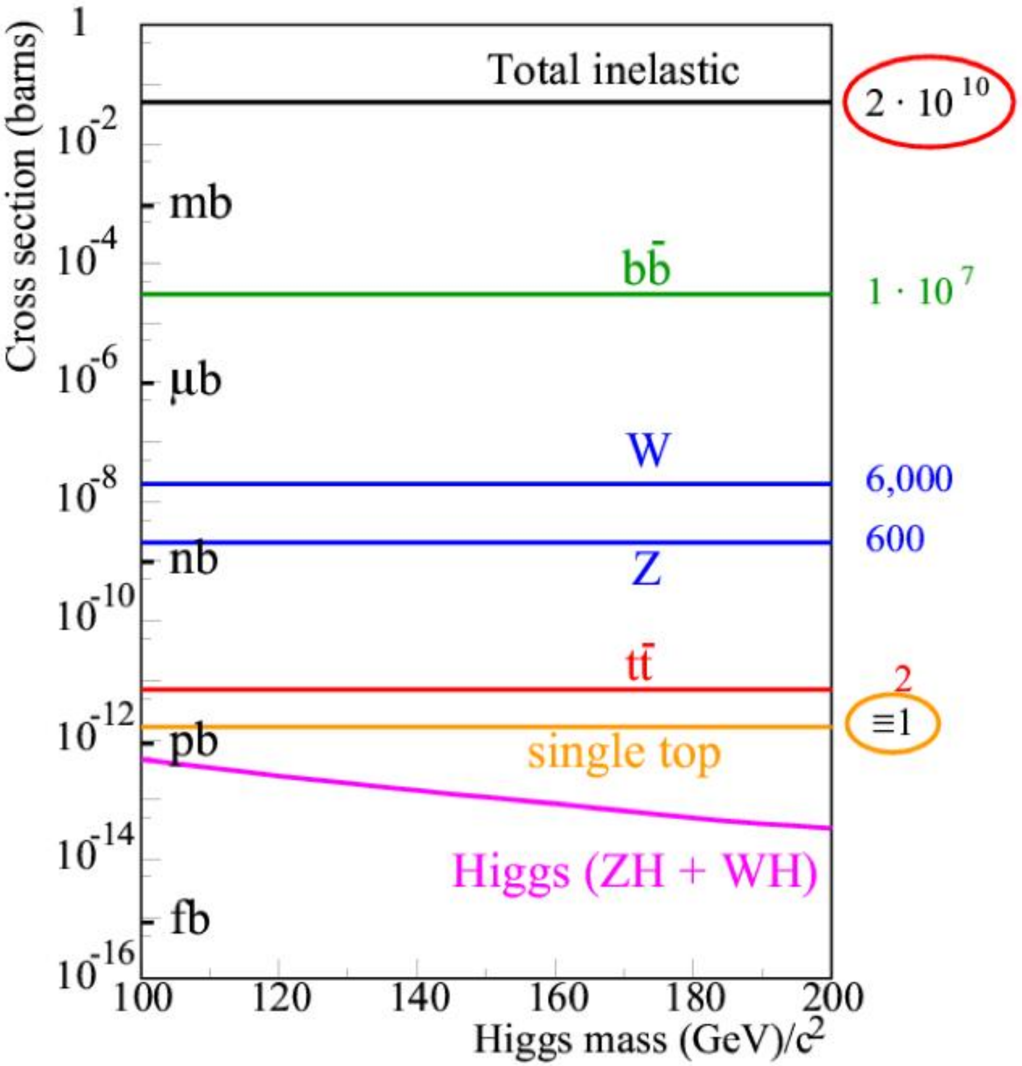
Top quark events are rare!



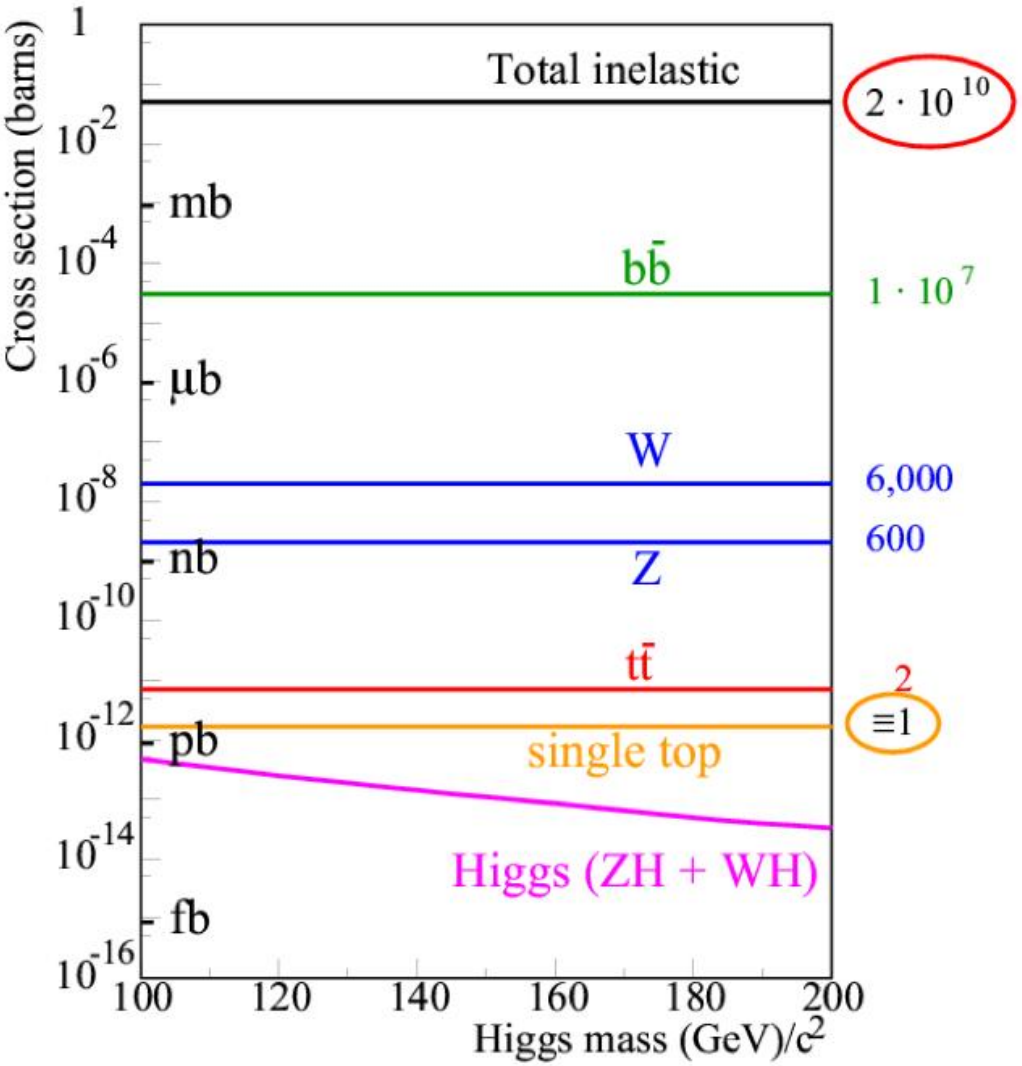
- Top production is a rare process: about one collision in every 1×10^{10} produces a Top-anti Top quark pair.

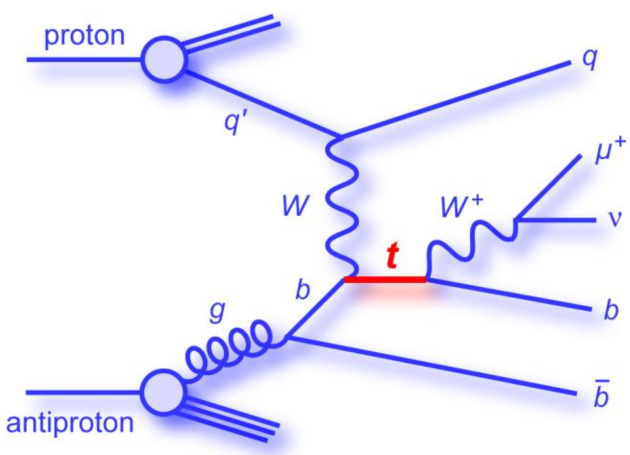
- Small cross sections require high luminosity, and the ability to detect and filter out Top-anti Top events from a large number of other processes with the same final states (backgrounds)

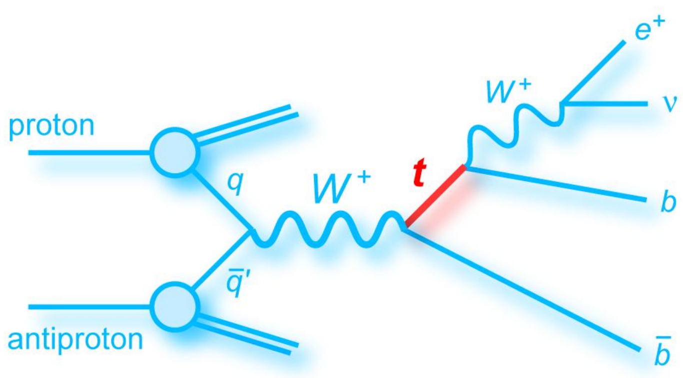
Single Top is even rarer



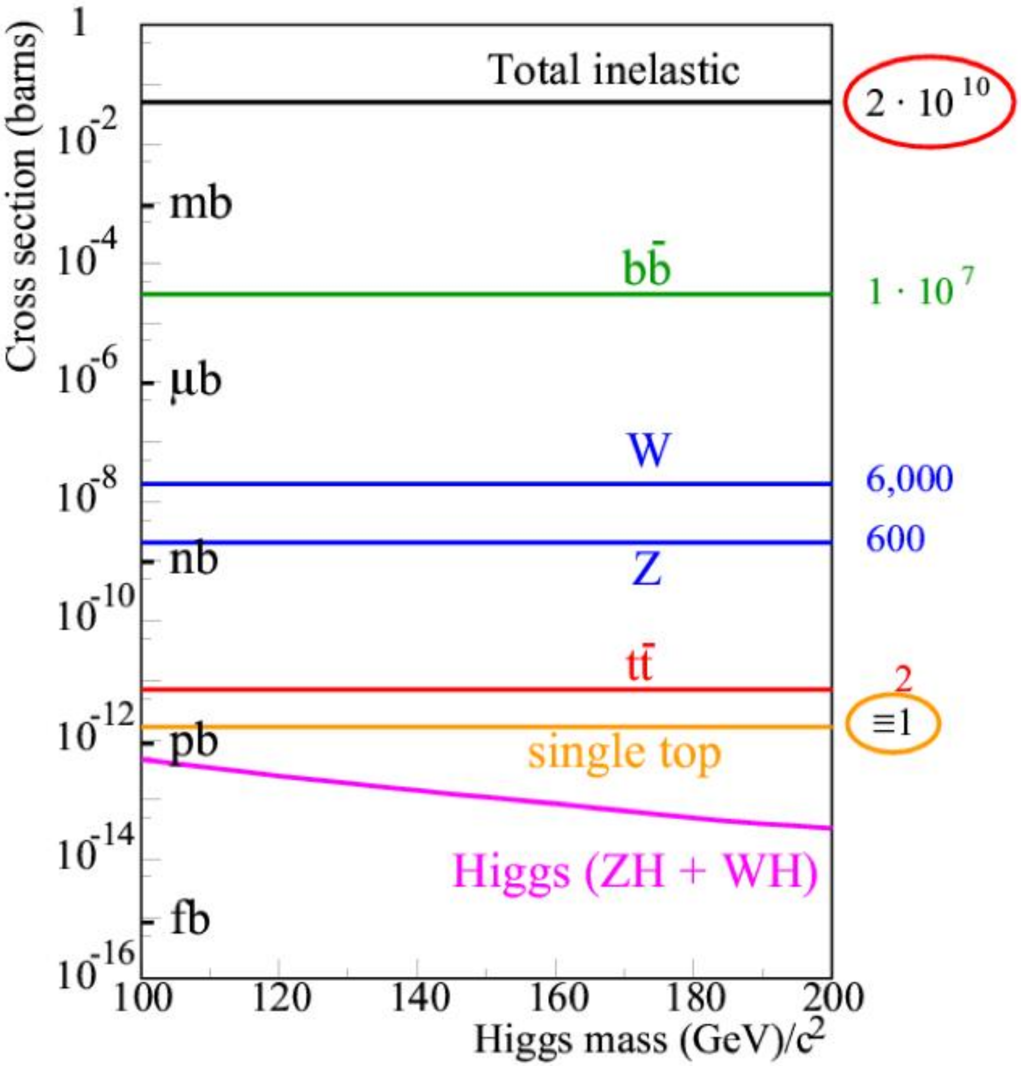
And has a less populated final state

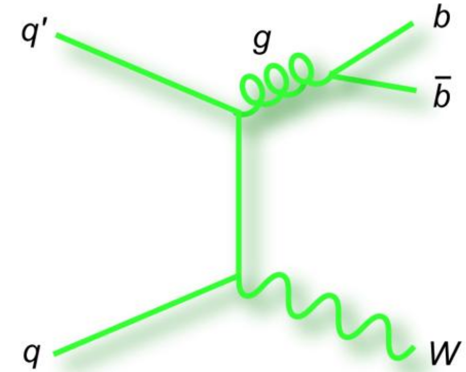


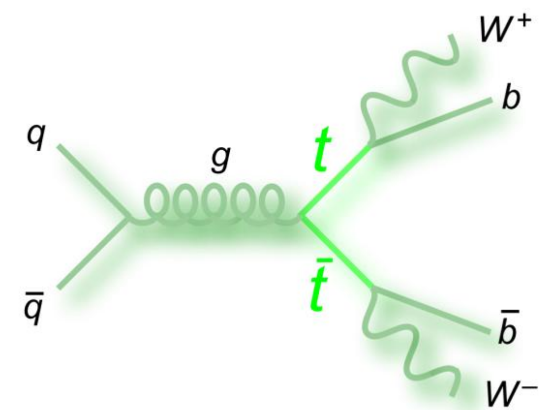




Experimentally very challenging







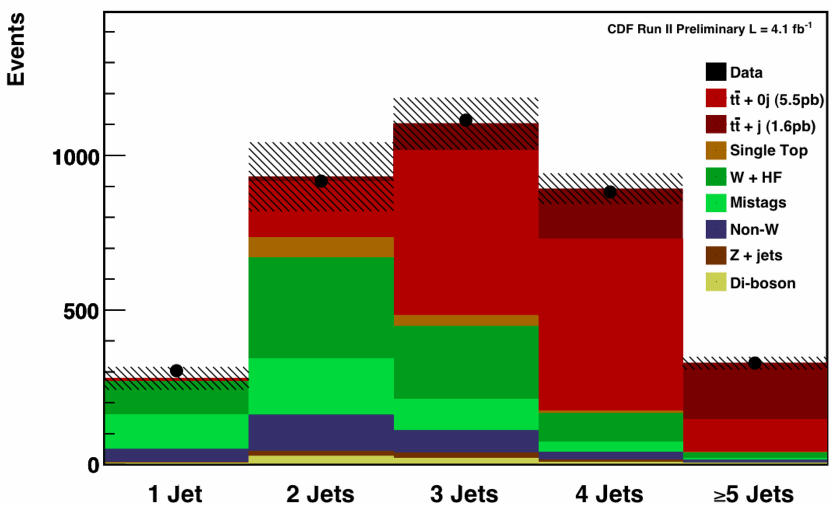
Recipe to measure a cross-section

Number of events that pass selection cuts

Number of events from processes other than top

Measured x-sec in channel X

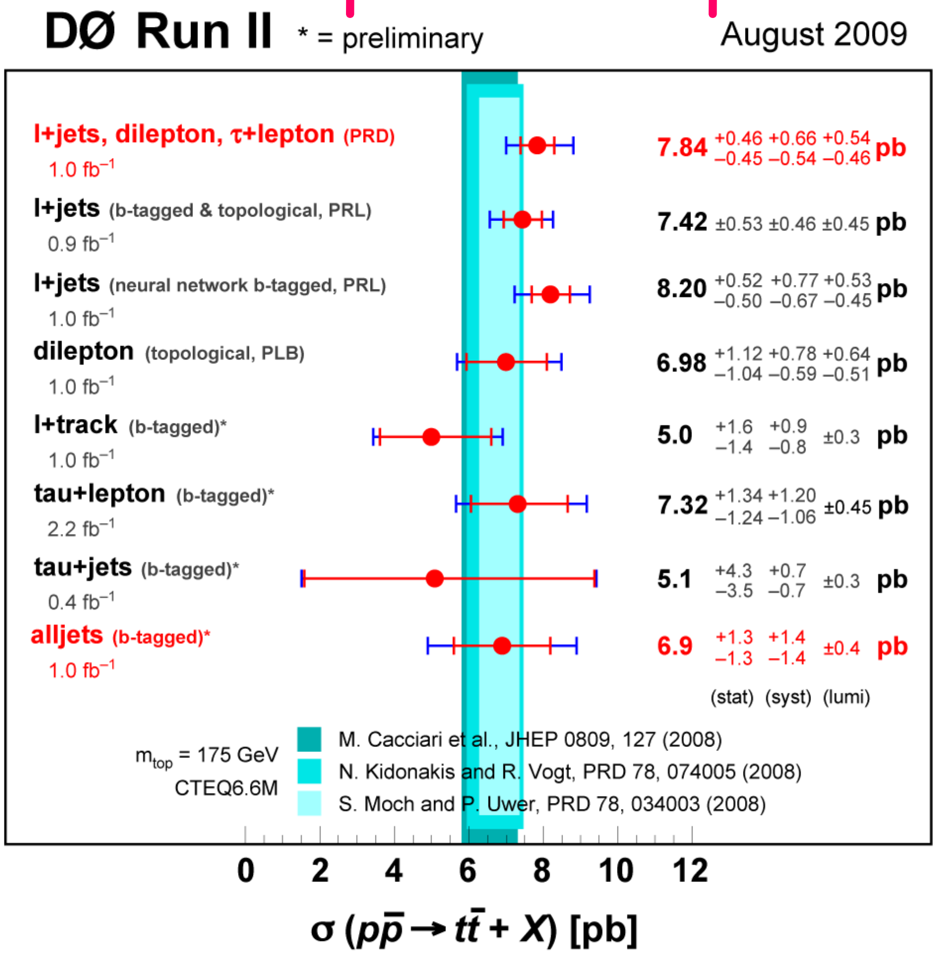
$$\boxed{\sigma(p\bar{p} \to t\bar{t} \to X)} = \frac{N_{obs} - N_{bkgd}}{\varepsilon * \mathcal{L}}$$

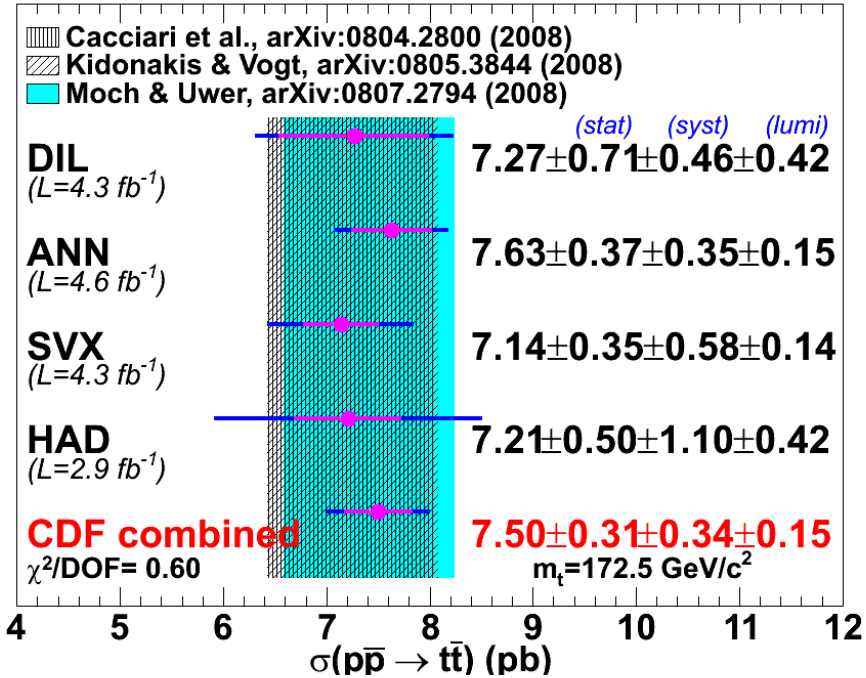


Integrated Luminosity: a measure of amount of data

Efficiency for top events

Top-anti Top x-section Measurement



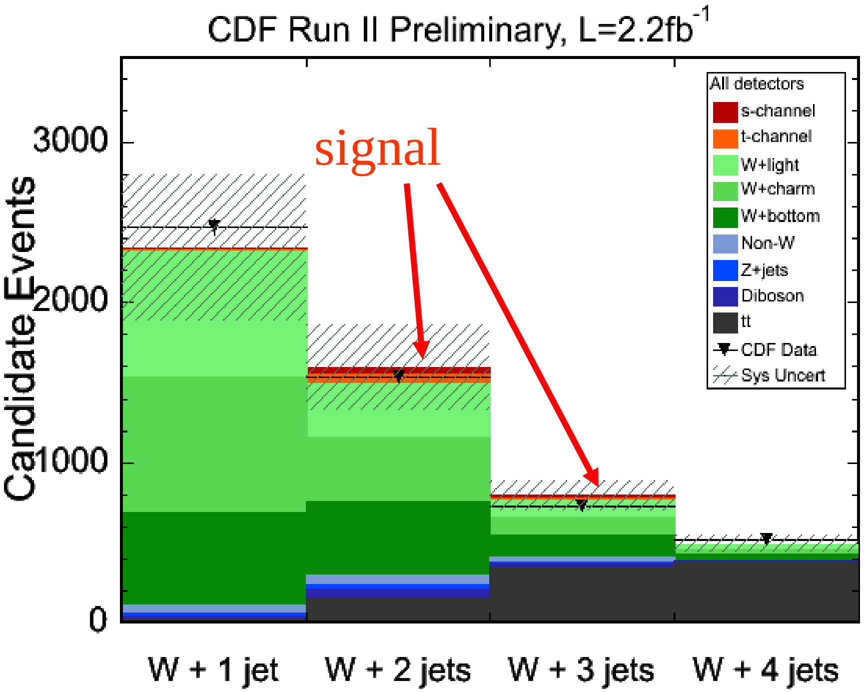


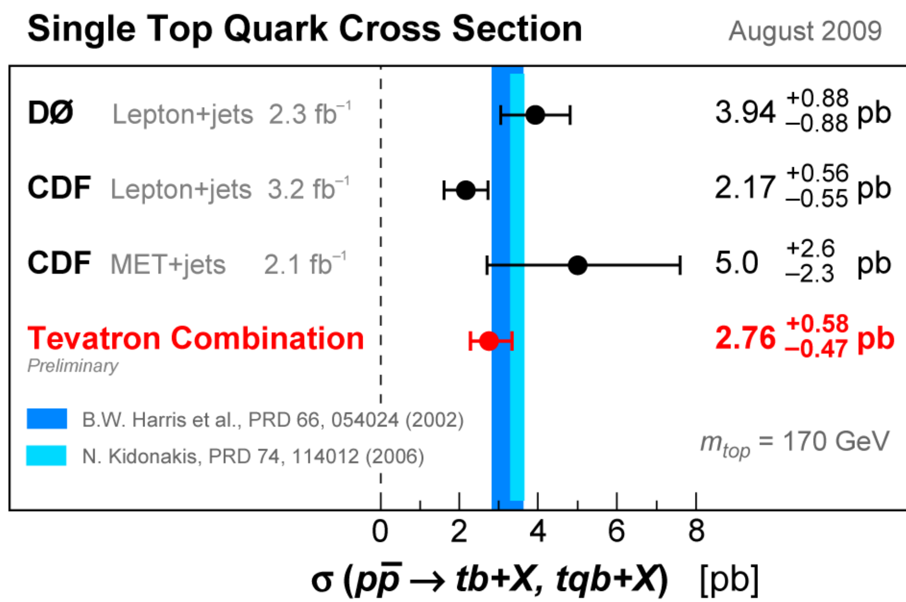
- Test of pQCD at high Q2
- Sensitive to new physics:
  - Expect higher x-sec if resonant or non-SM production occurs

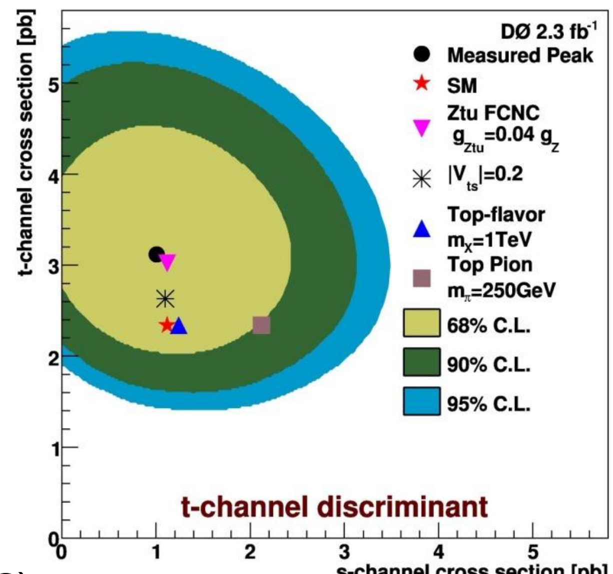
- Measure in different channels and with different techniques
  - b-tagging method assumes Br($t \rightarrow Wb$)=1
  - Kinematic fit methods are free of this assumption

Experimental uncertainties reaching precision in theoretical prediction.

Single Top Production

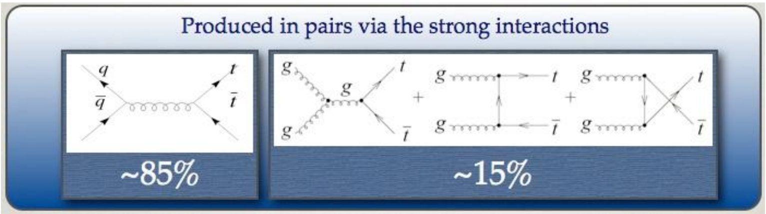


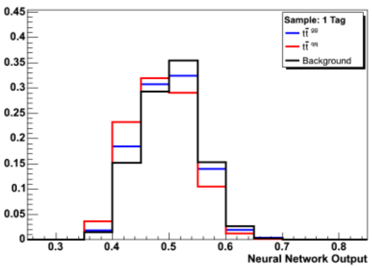


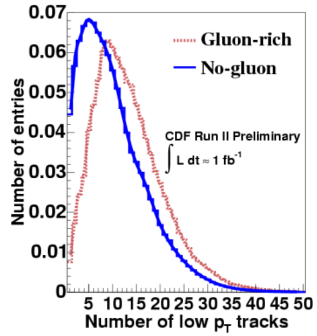


- Simple counting experiment cannot extract the signal from the background
  - Need advanced techniques
  - Multiple methods per experiment
    - Serve as cross check
    - Combination adds power

Top Quark Pair Production Mechanisms







Gluon Fusion Fraction

Measured with two orthogonal techniques: Track density multiplicity analysis & NN kinematic analysis

$$Fgg = 0.07 \pm^{0.15}_{0.07}$$

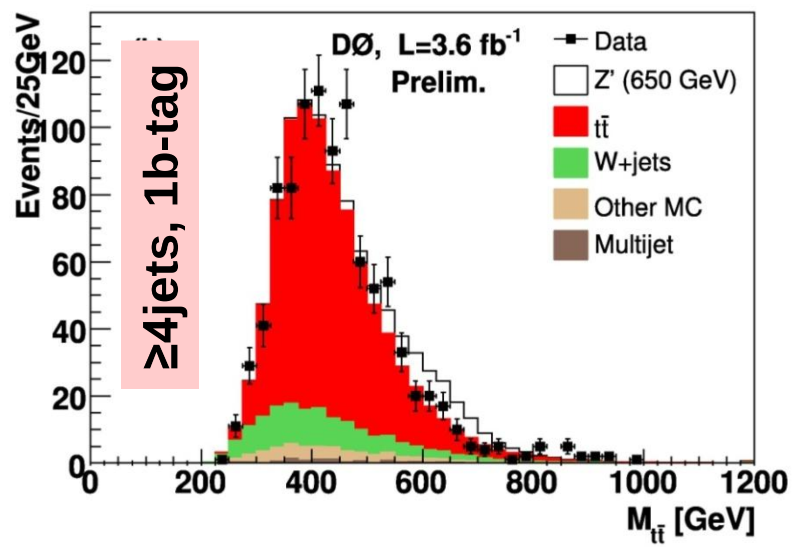
$$SM(pred) = 0.15 \pm 0.05$$

Uncertainty dominated by statistics

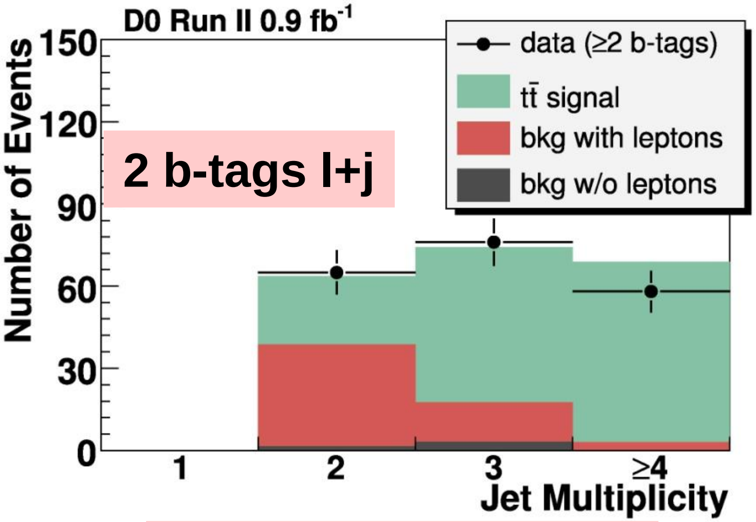
Search for ttbar resonances

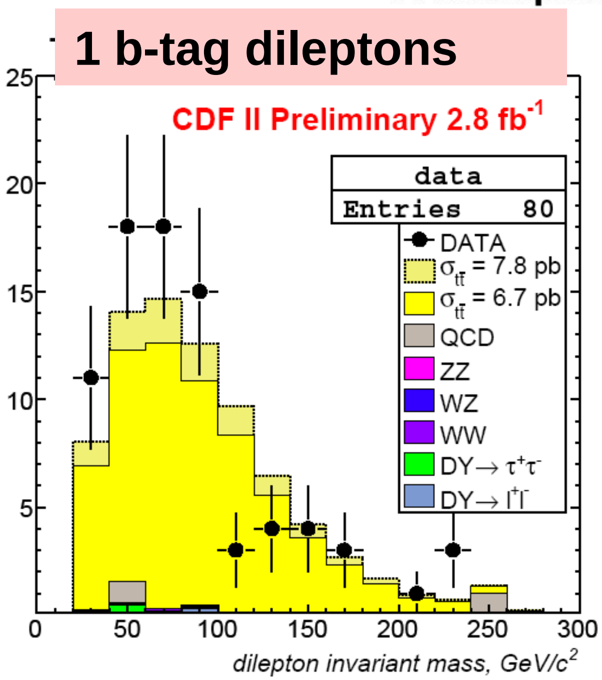
Study invariant mass spectrum of l+j events

No evidence for narrow resonance decaying into ttbar

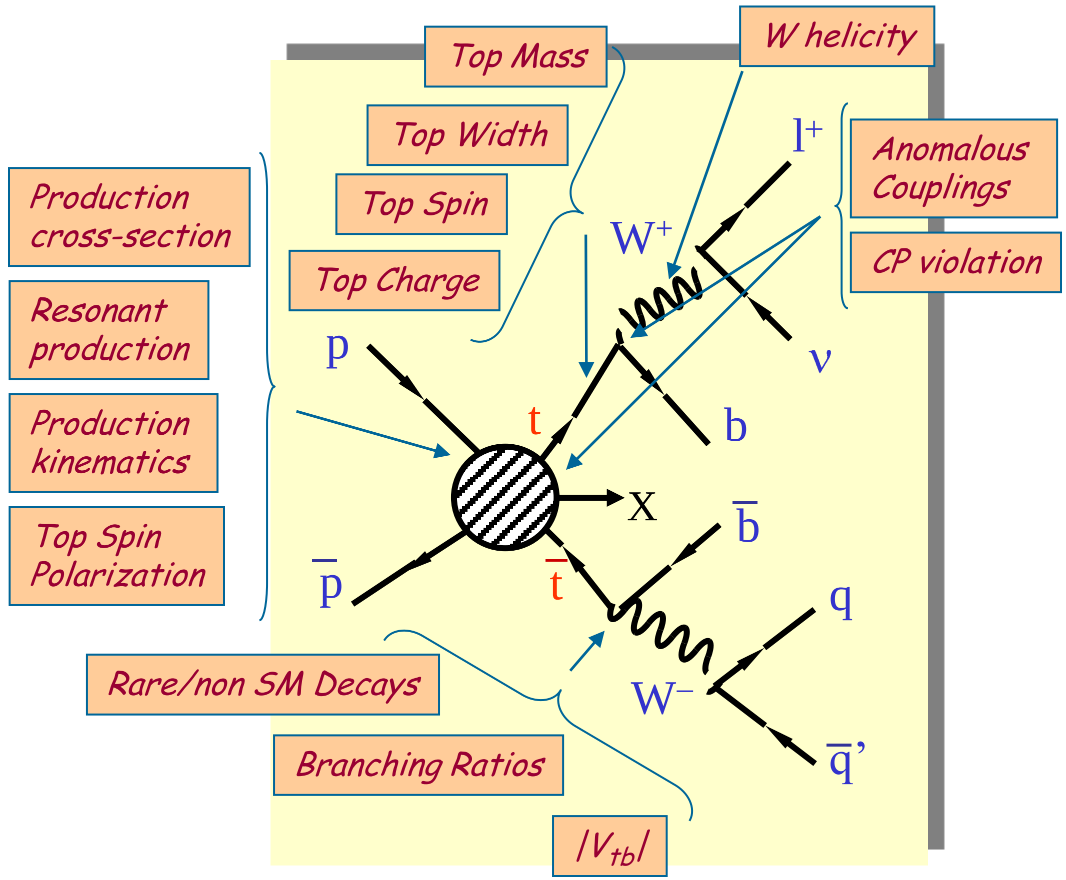


Top quark Properties

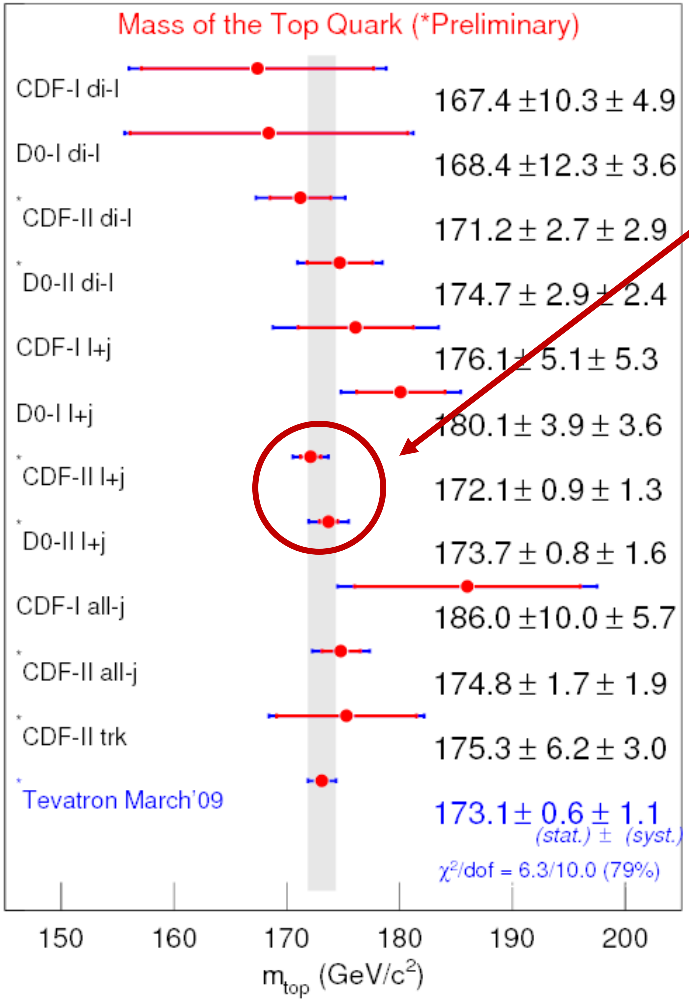




b-tagging provides pure sample of top quarks for properties measurements



Top quark Mass



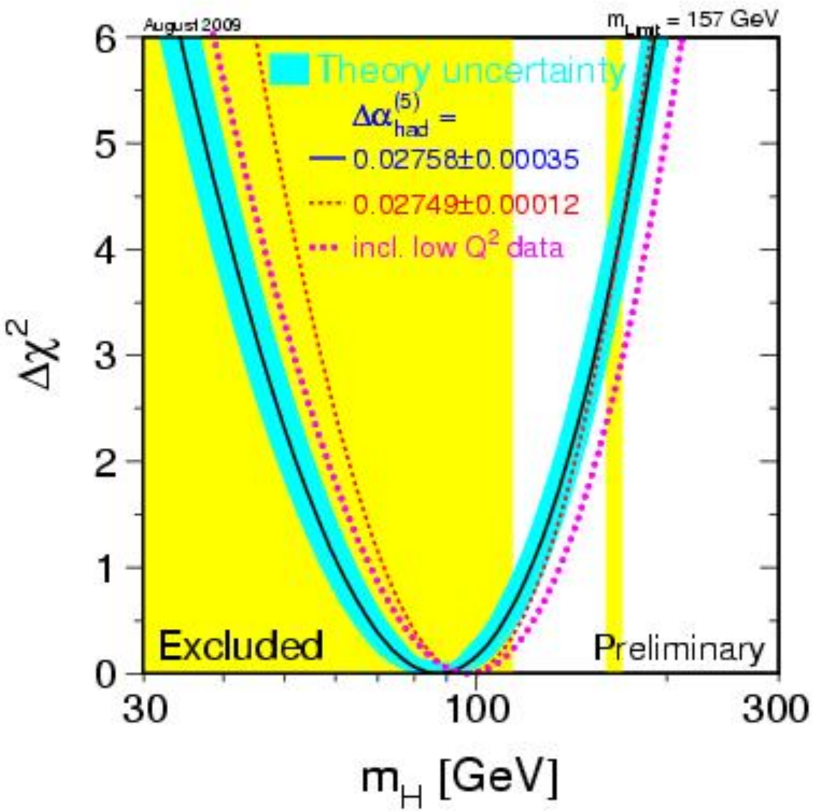
Best results (errors ~ 1%) obtained by ME Method:

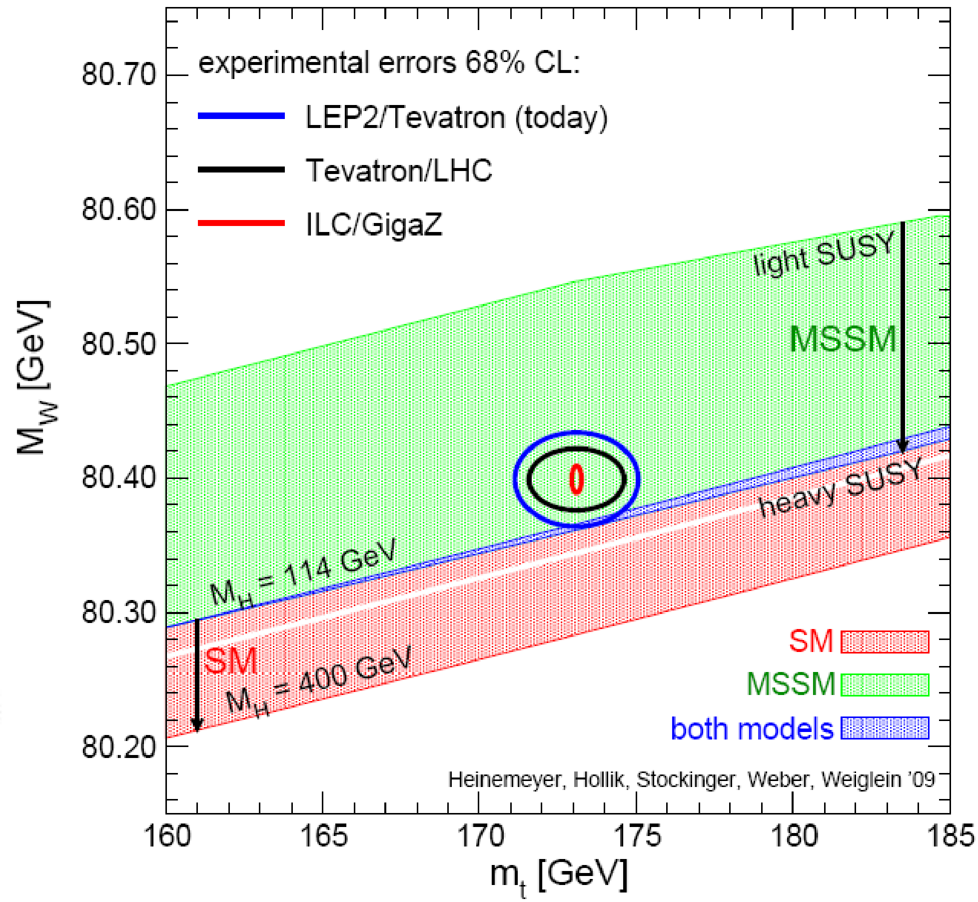
- Event by event weight calculated according to quality of agreement with SM top and background differential cross-sections
- Product of all event probabilities gives the most likely mass
- JES constrained in-situ by the hadronic decay of the W→jj

Dominated by systematics

M(top)=173.1±0.6±1.1 GeV

SM Constraints on the Higgs





$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$

$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$

$$m_H > 114 \text{ GeV(direct)}$$

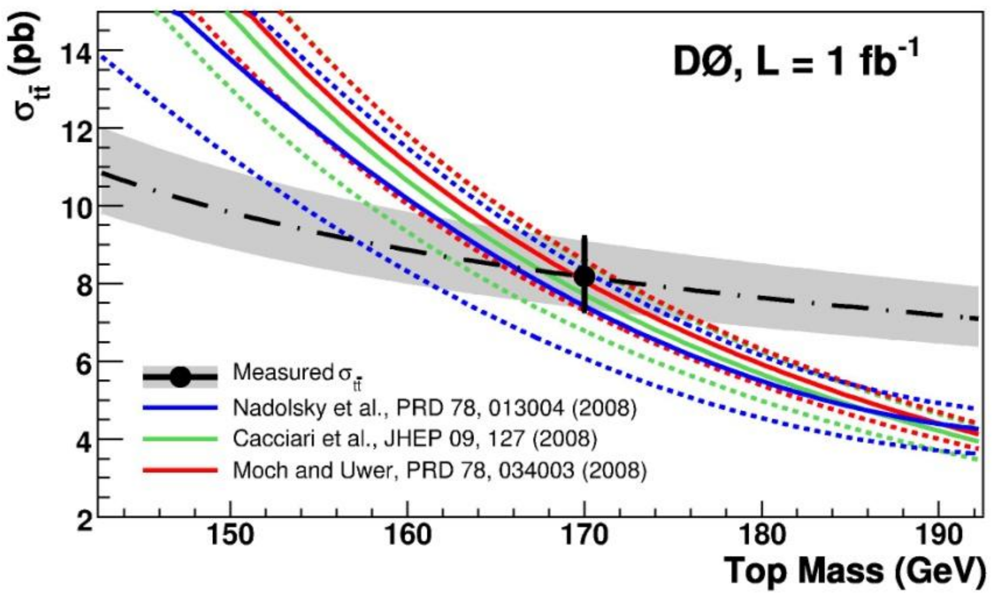
Light Higgs preferred by the SM with latest top and W mass

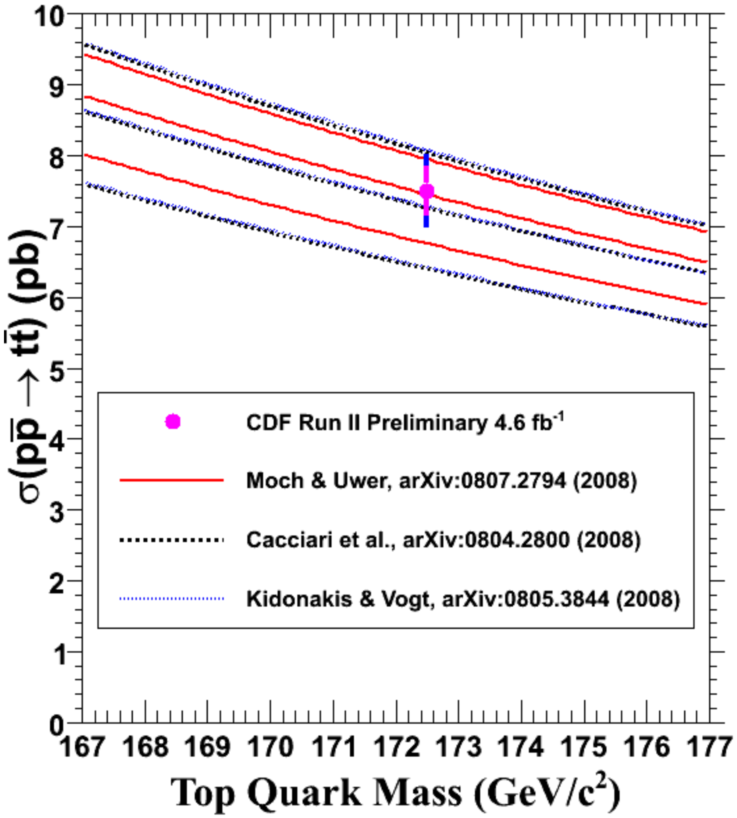
Plots from LEP/TEV EW working group

Top Mass from x-section

Assuming production is governed by SM, top quark mass can be extracted comparing the measured x-sec with theory

Measurement has different experimental and theoretical uncertainties than direct measurements.

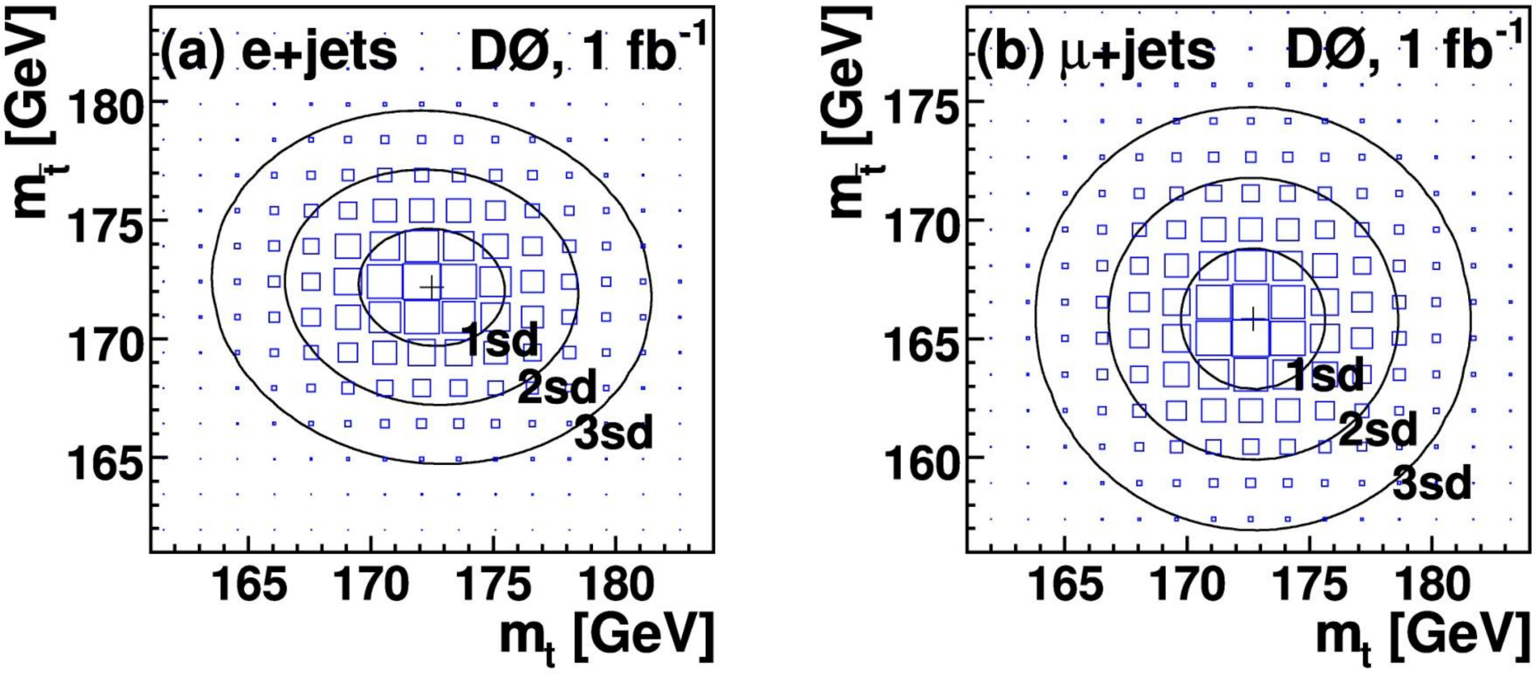




Both direct mass measurement and extraction from cross-section measurement agree within errors.

Top Anti-top Mass Difference

CPT invariance requires that the mass of particles and corresponding anti-particles be identical. Difficult to test with quarks because they hadronize before decaying. Not the case for top quarks.



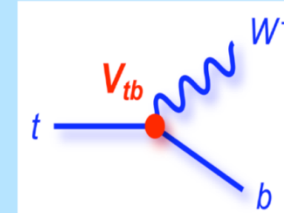
Measured Mass Difference = 3.8±3.7 GeV, consistent with zero

Top quark decay t→Wb

Weak interaction and mass eigenstates are not the same: mixing between quarks described by the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



General form of the Wtb vertex

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

SM:
$f_1^R = f_2^L = f_2^R = 0$
$f_1^L = 1$

SM predicts Vtb=0.9991

(unitarity and 3 generations)

Measure from the rate of b-jets in ttbar sample

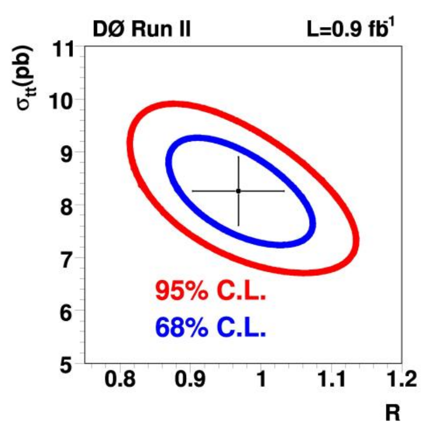
$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

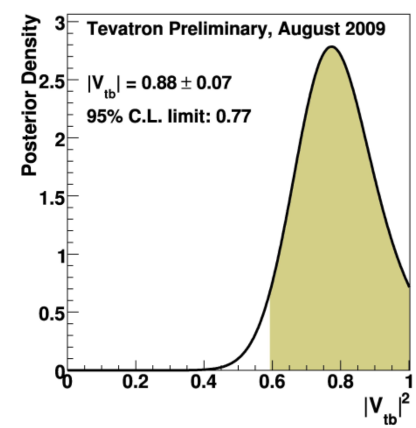
$|Vtb|^2$ directly proportional to single top production x-sec

$|Vtb|>0.89$ @ 95% C.L. (from R)

$|Vtb| >0.77$ @ 95% C.L. (single top)

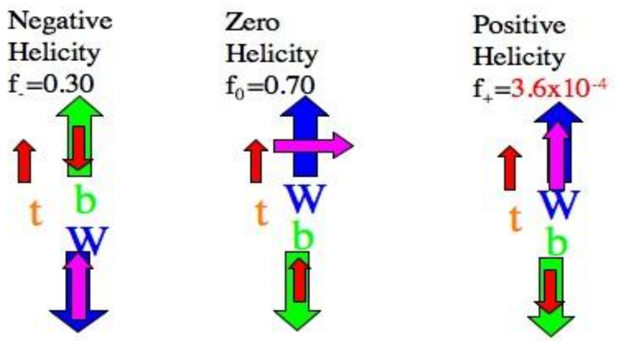
$|Vtb^*f_1^L| = 0.88 \pm 0.07$

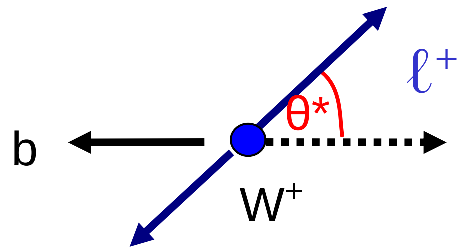




Decay Properties: W Helicity

Helicity: relative direction between the spin and the particle's motion.



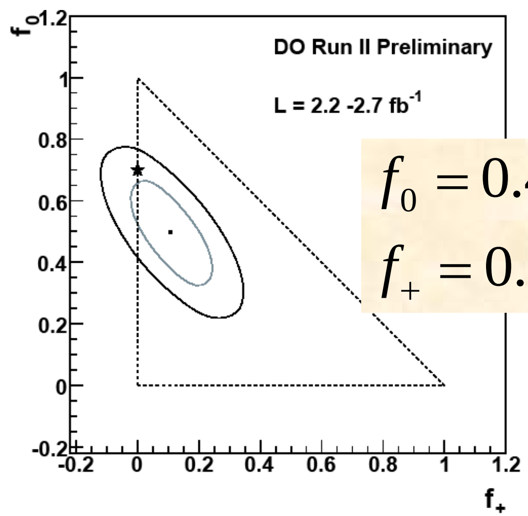


$\cos\theta^*$ used as sensitive observable

DØ: 2-parameter fit for fraction of longitudinal (f_0) and right-handed (f_+) polarized W bosons in ttbar decays

CDF: likelihood function for each event from ME for ttbar and W+j. Simultaneous determination yields

$$f_0 = 0.88 \pm 0.11 \pm 0.06$$
$$f_+ = -0.15 \pm 0.07 \pm 0.06$$



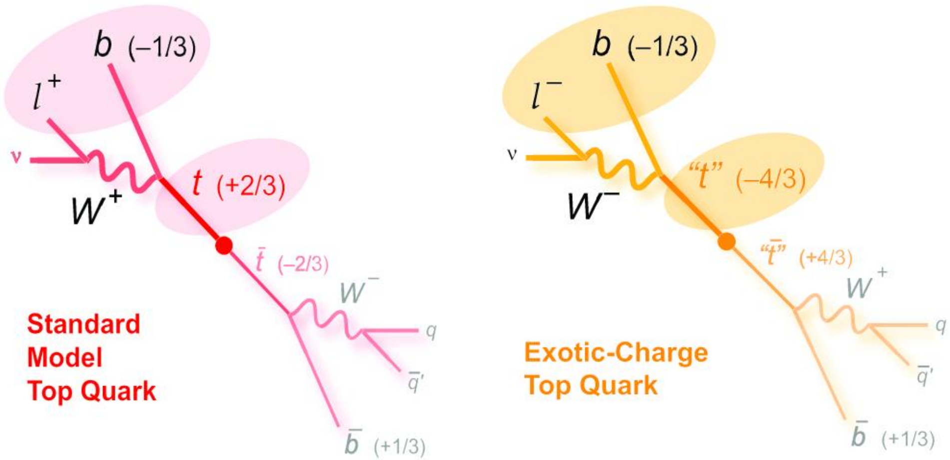
$$f_0 = 0.490 \pm 0.106 \pm 0.085$$
$$f_+ = 0.110 \pm 0.059 \pm 0.052$$

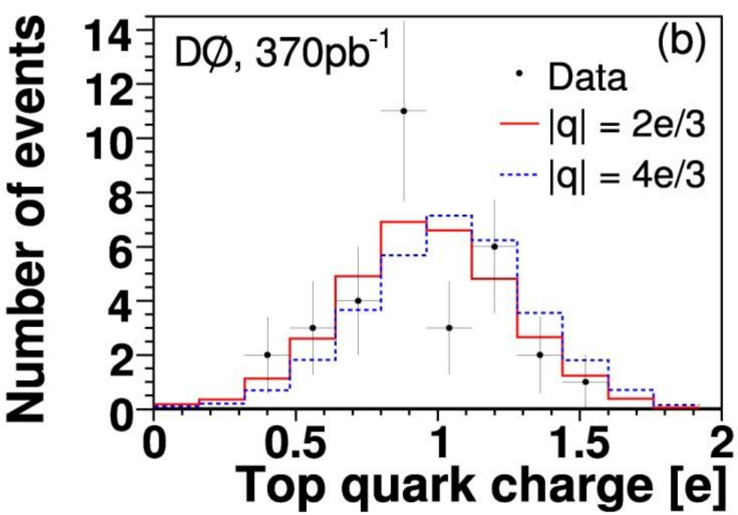
Statistically limited: consistent with the SM prediction.

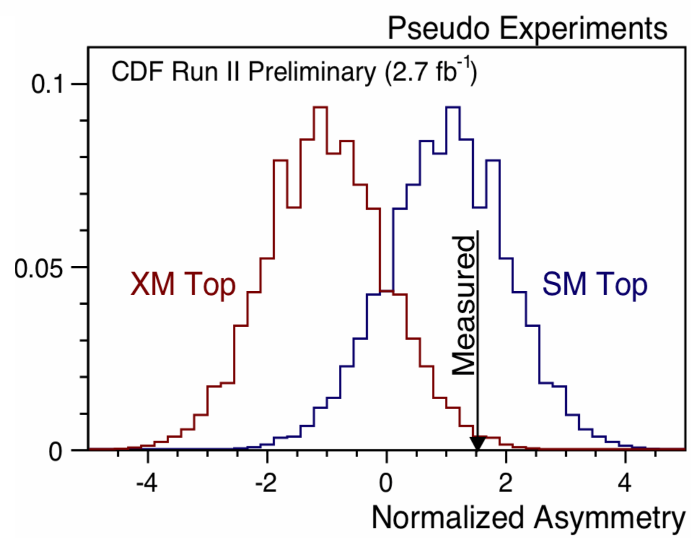
Top Quark Charge

- Fundamental property of particle
- One possible scenario

  Phys Rev D59, 091503 (1999):
  - **The discovered top quark is an exotic quark of charge - 4e/3**
  - **The top quark with charge 2e/3, mass 270GeV not observed yet**
  - **Model accounts for precision Z data (including R_b and A_{FB}^b)**







Statistically Limited!

Both CDF & DØ Data strongly favor the SM over XM

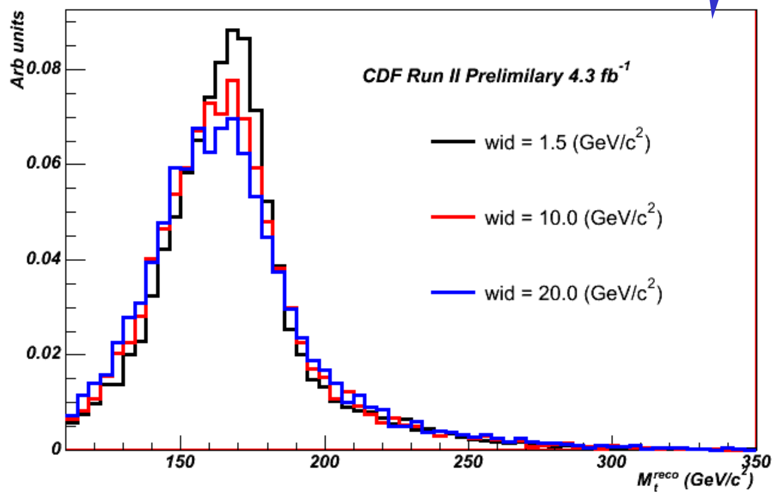
Top Quark Width

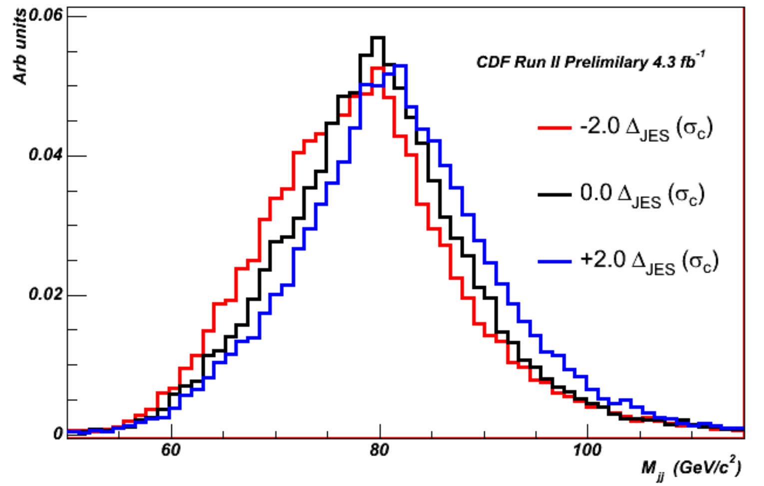
Γ_t^{SM} = 1.4 GeV, τ_t^{SM}=5x10^{-25}s

(for m_t = 175 GeV)

- Largest decay width (and shortest lifetime) of all quarks in the SM
- Deviations could indicate top decays to non-SM particles

• Width is extracted from lepton+jets events via a 2D template fit to the reconstructed top mass and the invariant mass of two jets from the hadronic W decay

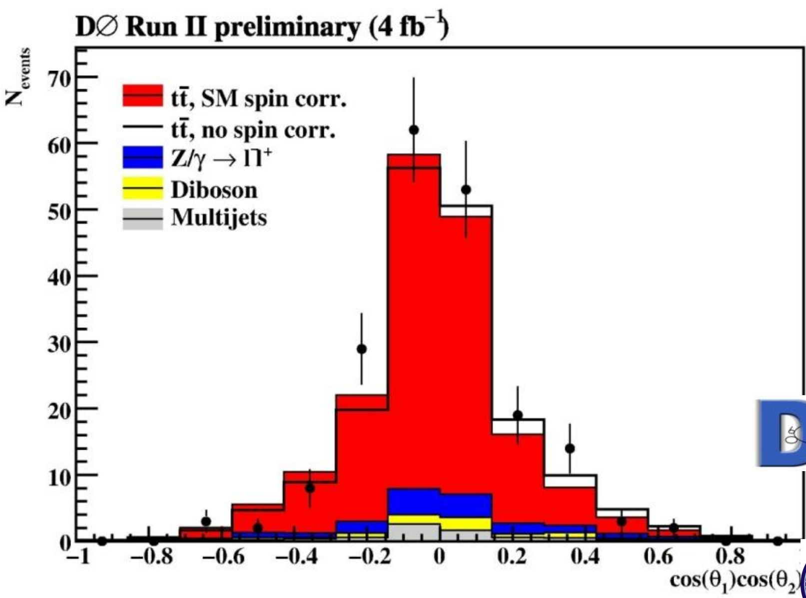




Γ_t< 7.5GeV @ 95% C.L, corresponding to τ_t>8.7x10^{-26}s

Top Quark Spin

- Top quarks decay before hadronization, transferring spin and kinematics to the final state
  - top quarks are produced unpolarized, but their spins are correlated
  - Study the spin correlation by analyzing the joint decay angular distribution of the top and the anti-top quark in dilepton events.



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

Angle between the lepton direction and the beam axis in the top rest frame.

$$C = -0.17 \pm^{0.64}_{0.53}$$

$$C = 0.32 \pm^{0.55}_{0.78}$$

Value depends on the spin basis

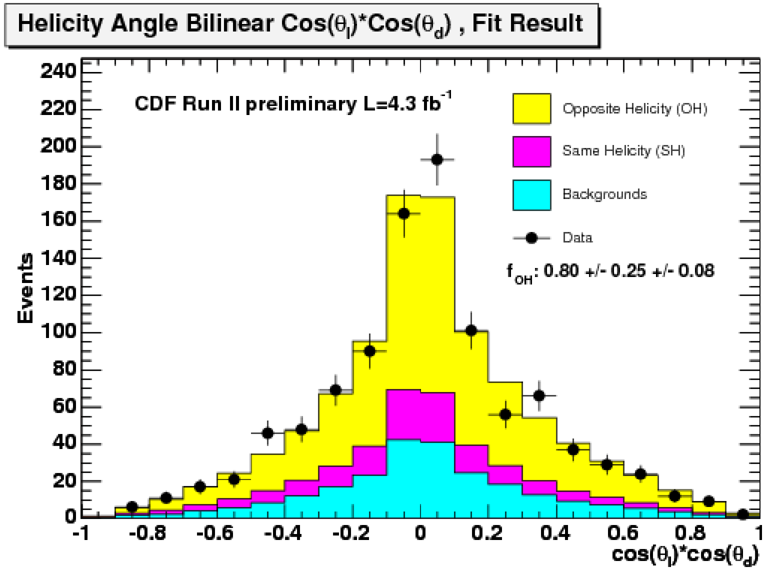
$$C_{SM} = 0.78$$

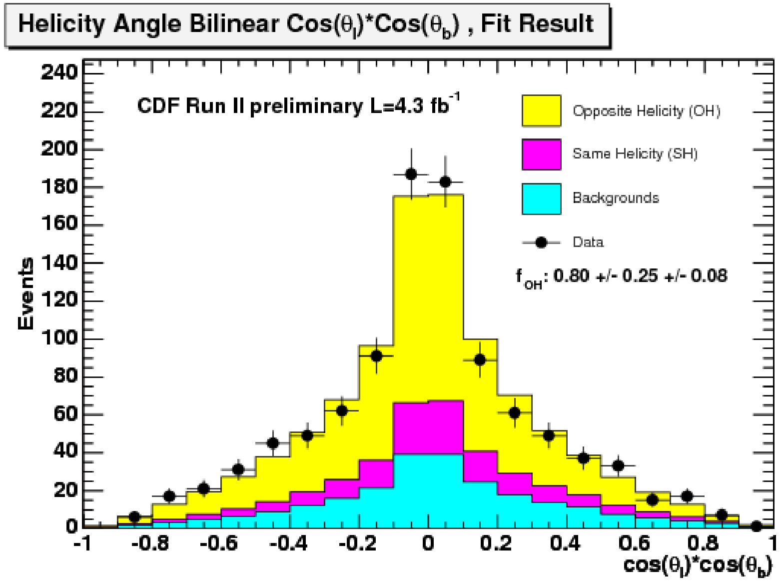
Measured correlation agrees with the SM within 2SD

Top Helicity and Spin Correlations

New! New!

- Measured in reconstructed lepton+jet events, using the correlations of leptons, b-jets and identified d-jets.
  - 2-D fit to the helicity angle bilinears $\cos(\theta_l)\cos(\theta_d)$ vs $\cos(\theta_l)\cos(\theta_b)$





Opposite helicity fraction $f_0 = 0.80 \pm 0.25 \pm 0.08$

Spin Correlation coefficient $\kappa = 0.60 \pm 0.50 \pm 0.16$

measured in the helicity basis

Novel method benefits from the larger stats of the l+j sample

MANY Searches for BSM effects

- Using top pair final states:
  - SM H→b anti-b in association with top (Htt-bar)
  - Top decay to charged Higgs $B(t \to H^+ b)$
  - Scalar Top pair production
- Using single top final states
  - $H^+ \to tb$ search
  - Anomalous Wtb couplings
  - W'→tb search
  - FCNC search

All results agree with the SM expectations…

After ~15 years of studies

- m_t=173.1 ± 0.6(stat) ±1.1(syst) GeV
- $\Delta_m = m_t - m_t$ = 3.8±3.7 GeV

- σ(tt)=7.84±0.95pb (for m_t=175GeV)
- σ(tt)=7.50±0.48pb (for m_t=172.5GeV)
- σ(t)=2.76+0.58-0.47pb (for m_t=170GeV)

- $|V_{tb} f_1^L|$ = 0.88 ± 0.07
- Charge: -4/3 excluded @ 95% CL
- Γ_t < 7.5 GeV @ 95% CL, $\tau_t > 8.7\times10^{-26}$s

- Longitudinally polarized W:
  f_0=0.49–0.88 [f_0(SM)=0.7]
- Opposite top helicity fraction
  f_0=0.80±0.25±0.08 [f_0(SM)=0.7]
- Top spin correlations
  agreement with the SM for spin ½ top

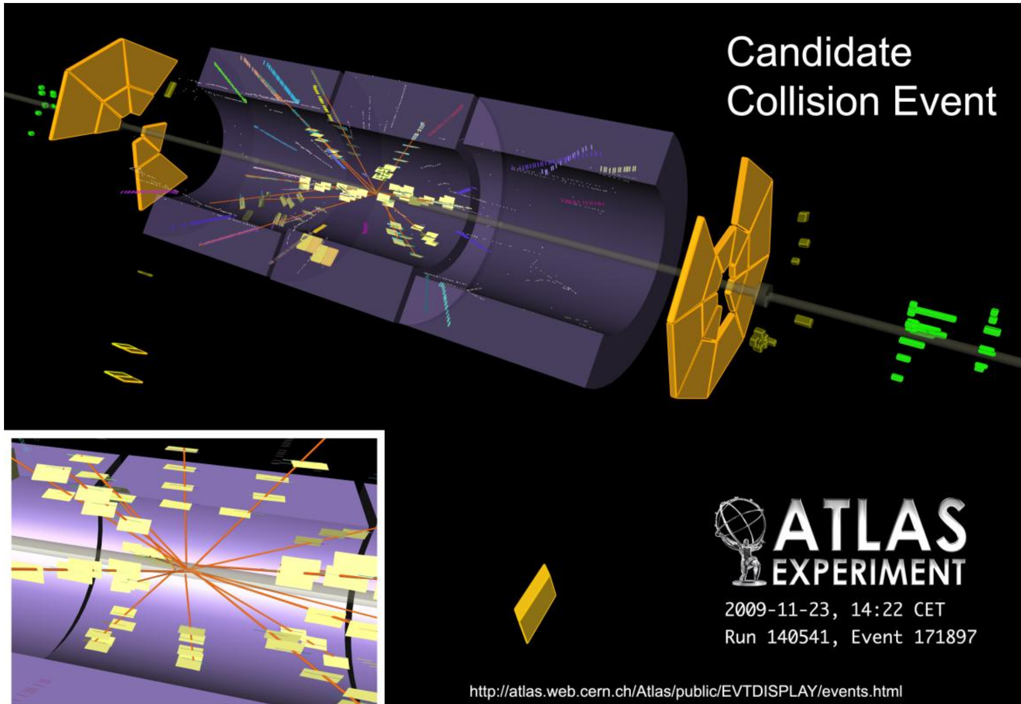
plus MANY limits on new physics

http://www-cdf.fnal.gov/physics/new/top/top.html

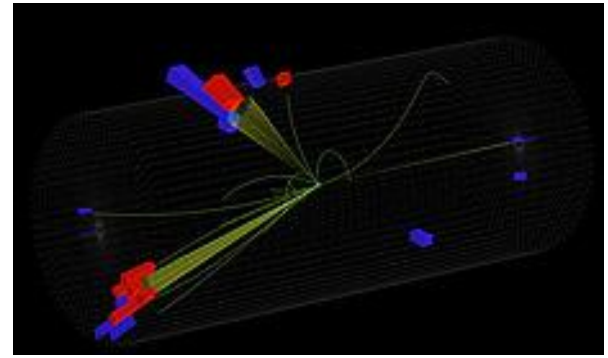
http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

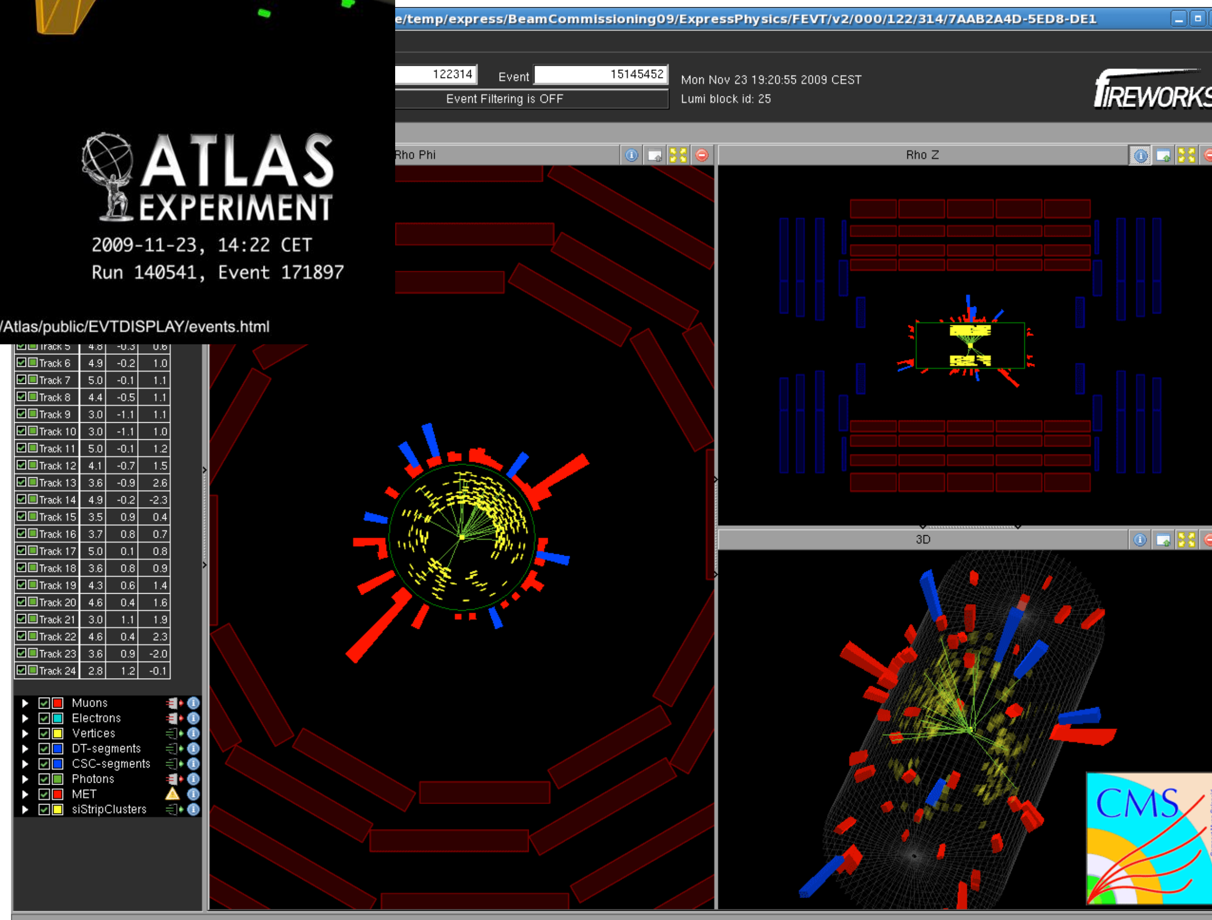
Conclusions

- Tevatron Run2 is an ongoing success… $8fb^{-1}$ delivered and $\sim 12fb^{-1}$ expected (2011)
- LHC startup imminent, plans to collect $1fb^{-1}$ of data at 7 TeV. Will result in a sample of top quarks comparable in size to the entire Tevatron Run II dataset.
- The next few years promise to be a very exciting time in the field of high energy particle physics.



Candidate Collision Event
ATLAS EXPERIMENT
2009-11-23, 14:22 CET
Run 140541, Event 171897
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html





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Mon Nov 23 19:20:55 2009 CEST
Event Filtering is OFF
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FIREWORKS
Rho Phi
Rho Z
3D
Track 6 4.9 -0.2 1.0
Track 7 5.0 -0.1 1.1
Track 8 4.4 -0.5 1.1
Track 9 3.0 -1.1 1.1
Track 10 3.0 -1.1 1.0
Track 11 5.0 -0.1 1.2
Track 12 4.1 -0.7 1.5
Track 13 3.6 -0.9 2.6
Track 14 4.9 -0.2 -2.3
Track 15 3.5 0.9 0.4
Track 16 3.7 0.8 0.7
Track 17 5.0 0.1 0.8
Track 18 3.6 0.8 0.9
Track 19 4.3 0.6 1.4
Track 20 4.6 0.4 1.6
Track 21 3.0 1.1 1.9
Track 22 4.6 0.4 2.3
Track 23 3.6 0.9 -2.0
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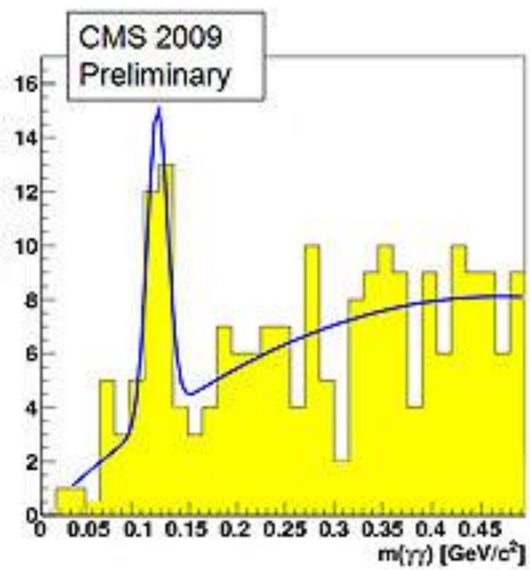
Muons
Electrons
Vertices
DT-segments
CSC-segments
Photons
MET
siStripClusters
CMS



CMS 2009
Preliminary
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0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45
m(γγ) [GeV/c²]